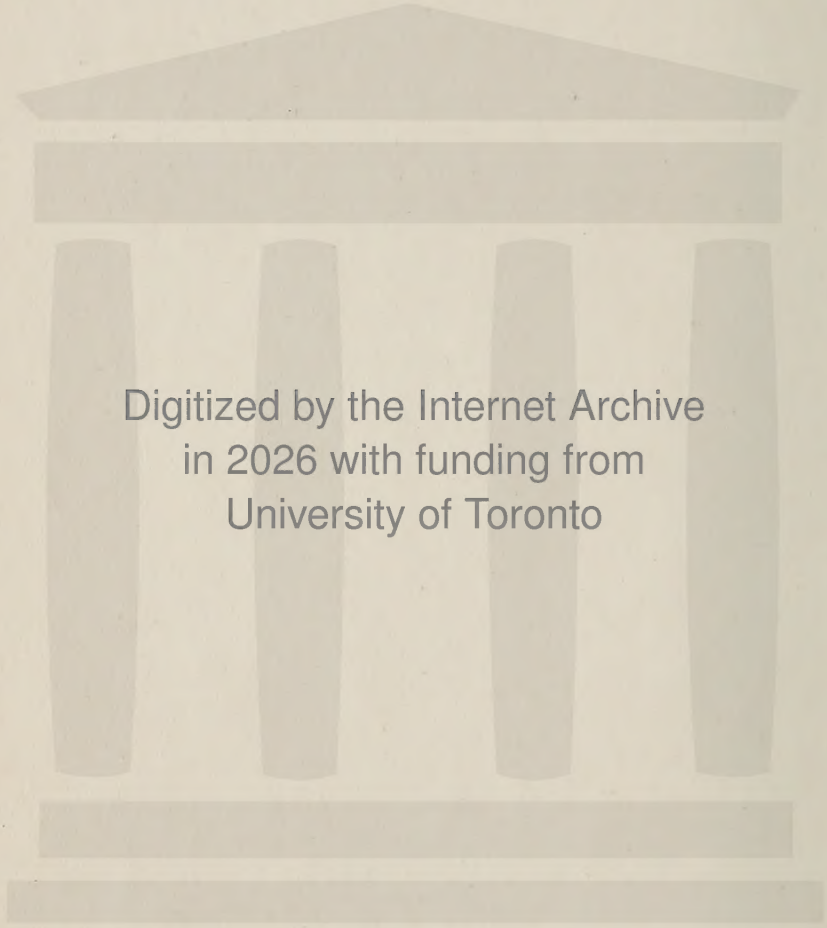
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THE UNIVERSE

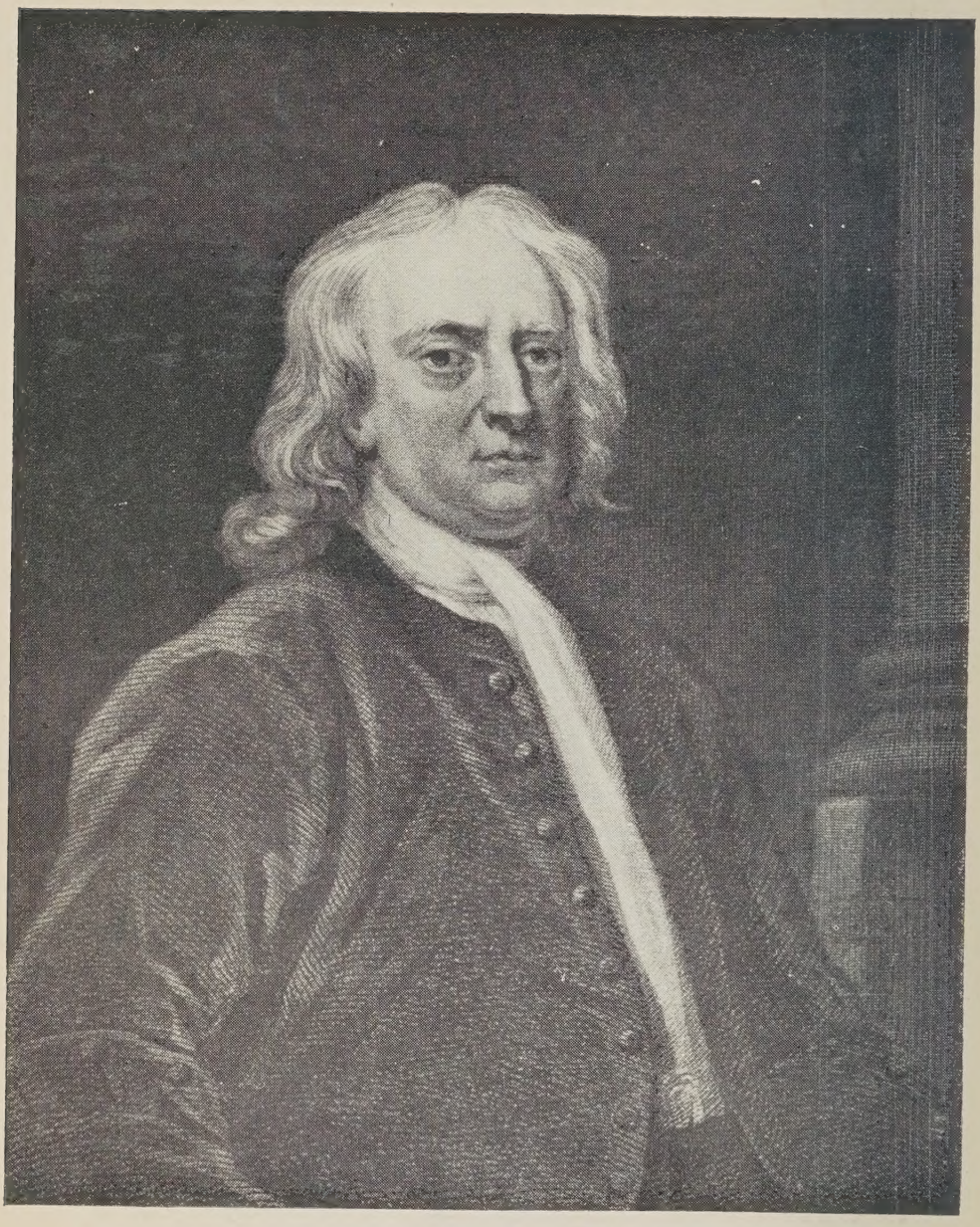

Fig. 11. Newton *Frontispiece*

Astron
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THE UNIVERSE

FROM CRYSTAL SPHERES TO RELATIVITY

BY

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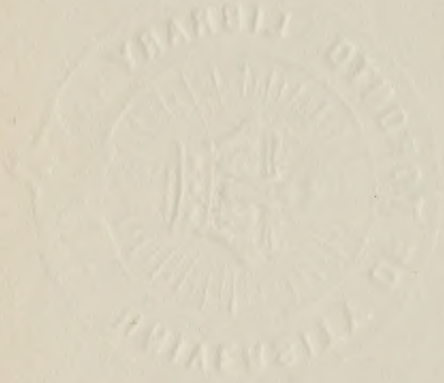

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TO MY EMINENT FRIEND,

THE HONOURABLE ALEXANDER CASIMIR GALT,

JUSTICE OF THE COURT OF THE KING'S BENCH, MANITOBA,

THIS LITTLE BOOK IS DEDICATED

AS A MARK OF ESTEEM AND APPRECIATION OF

MANY DELIGHTFUL CONVERSATIONS ON THIS

AND KINDRED THEMES

TRUTH

ALREADY see! she opes the Gate of Day!
The Lists I enter, and pursue my Way!
The Massy[1] Whirlpools, heaving still for Place,
Heap'd without Rule, and moving without Space,
Those learned Phantoms vanish from my Sight,
And Day[2] comes on me with her genuine Light!
That vast Expanse, of Being the Abode,
Space, which contains th' Infinity of God,
Sees in her Breast this bounded System move
Of Planets, Worlds, beneath us and above,
Whose whole Extent, so wondrous to our Sense,
Is but a Point, an Atom in th' Immense.

VOLTAIRE

From a translation of part of the dedication in his essay on Sir Isaac Newton's philosophy.

[1] The cosmogony of Descartes.
[2] The Newtonian system of the world.

THE Name of new Philosophy would be no more than the Title of a new Romance, if it implied only the Conjectures of a Modern in opposition to the Notions of the Ancients. A Philosophy, founded only upon accidental Explications advanced at a venture, would not in strictness deserve the least Examination. For the Methods of arriving at Error are innumerable, whilst there is but one way that leads to Truth ; it is therefore the odds of infinite to one, that a Philosopher, who supports his Principles only by Hypotheses, will advance nothing but Chimeras. Hence it is, that all the Ancients, who have treated Physics without the light of Experiments, have been only the Blind explaining the Nature of Colours to the Blind.

VOLTAIRE

FOREWORD

THIS lecture was delivered as the first of the twenty-second series, 1928, of February Popular Lectures in the University of Manitoba. In selecting the subject of relativity for this occasion the committee believed the public generally desired information on the great and far-reaching intellectual developments of the time rather than the more entertaining aspects of popular experimental science.

It was not a little surprising as well as highly gratifying to find a "capacity" audience of seven hundred people eager to discover the novel ideas involved in the new way of looking at the physical universe which are comprised in the theory of relativity. So interested an audience deserved a better treatment of a subject much of which is abstruse and abstract in comparison with the ideas of our normal intellectual life. The fact that they were deeply attentive to a lengthy lecture induced

me to publish it. In doing so I have somewhat amplified the material but retained the lecture style. I have included a few portraits, and added diagrams for the elucidation of the argument.

It is hoped that this lecture will be found sufficiently short to be read through at one time and thus enable the reader to obtain quickly a brief general sketch of the subject. In gathering material I have consulted a number of works, as those acquainted with the literature will at once recognize. I myself have been influenced most of all by the writings of Einstein, Eddington, Thirring, and Haas. It would be too much to hope that I have escaped falling on some of the slippery paths of relativity. If the ideas of relativity were self-evident or if they could be grasped without effort, the theory would evidently not be sufficiently novel to deserve much consideration. Fundamentally relativity involves a new method of thinking of the ordinary concepts of physical science. The revolutionary ideas are so different from those to which we have become accustomed

that upon first meeting with them one experiences much confusion of mind.

Any one, I imagine, who expects to grasp the significance of relativity in one lecture or by the perusal of a single popular book will be greatly disillusioned and even discouraged. Clarity of perception requires the reading and re-reading of books at intervals sufficiently far apart to allow time for the new ideas to become incorporated as a part of one's mental equipment.

On this occasion relativity is considered as a new conception of the world. Primarily it is a new system of physics; yet any theory of physics which alters so profoundly our views of matter, motion, energy, space, time, and gravitation cannot avoid being also a distinctive system of the world. Popular interest, it can scarcely be doubted, is in such a view of relativity, and I have accordingly presented the subject from that standpoint. In falling far short of my ideal of an attractive presentation of a novel scientific subject, I have to confess that "every hand is not capable of covering the thorns of the sciences with the flowers of wit and fancy."

FOREWORD

I am greatly indebted to several friends, particularly Professors L. Gilchrist and E. F. Burton of Toronto University and Mr. R. W. Wydeman, Mr. A. H. A. Lasker, and Rabbi Solomon Frank of this city, for reading this lecture and suggesting improvements.

University of Manitoba,
Winnipeg, Canada.

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THE UNIVERSE

FROM CRYSTAL SPHERES TO RELATIVITY

THE latter part of the year 1918 and the first part of the year following are memorable for two events of extraordinary interest and importance. Widely different in character as are the triumphs of peace and war, they were alike in marking the close of old and the opening of new epochs in history and science. The earlier event was the termination of a war of unparalleled proportions and significance. The second was the departure of two small parties of astronomers from England, one for Sobral in Brazil, the other for the island of Principe off the west coast of Africa, to observe the total eclipse of the sun on May 29, 1919, which was visible at those places. The astronomical expeditions attracted little attention until their reports in the latter part of the year excited a popular as well as a scientific interest of so sensational a character as to be almost unpre-

cedented in the history of science. From that time Einstein and his theory of relativity have held the attention of all who are interested in the development of our knowledge of the material world.

In observing this historic eclipse the astronomers were not concerned with the examination of the sun itself. Their purpose was concentrated upon obtaining photographs of the bright stars near its surface when they sprang suddenly into visibility in the short interval of darkness during the eclipse. These photographs were to be compared with others of the same stars taken with the same equipment some months earlier when the sun was in another part of the sky. By this means the astronomers hoped to verify the prediction of Einstein that in the eclipse photographs the star-images would be farther apart than they were in the others.

Since the stars are situated at enormous distances from the sun and are therefore far beyond its influence, it is clear that they cannot possibly have their real positions altered in the slightest degree by the temporary presence of the sun in the stellar

line of vision. From his theory of relativity Einstein had shown that the rays of starlight passing near the sun would be deflected or curved toward it by the action of its powerful gravitational attraction. This slight inward change of direction

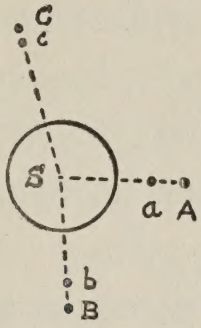

Fig. 1. Apparent displacement of stars from their real positions a, b, and c to A, B, and C, due to the deflection of the rays of starlight by the gravitational attraction of the sun, S. The star a, nearest the sun, is displaced most; and c, the most distant, is displaced least.

of a ray of starlight will cause an apparent displacement of the star away from the sun in the direction of the straight line joining it with the centre of that body.

The effect may be shown on a greatly enlarged scale by means of a diagram (Fig. 1). The real positions of the stars are represented by a, b, and c.

But when the sun, S, is present, the rays of starlight passing near its surface are attracted toward its centre, and as a consequence of the deflection of the light the stars appear to be displaced outward to the positions A, B, and C.

The reason for this occurrence is shown in the

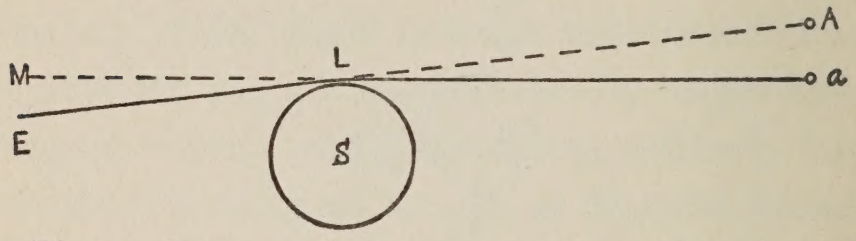

Fig. 2. Apparent displacement of a star from its real position, a, to A, due to the deflection of the ray of light at L which causes it to proceed to the observer at E. The apparent position of the star is in the straight line ELA.

second diagram (Fig. 2). The real position of a star is indicated by the letter a. E is the position of an observer on the earth, and S is the eclipsed sun. A ray of starlight going directly toward the observer is obviously stopped by the sun. But the ray, aL, which grazes its surface at L, is deflected or curved toward it by the gravitational attraction of the huge solar mass, and the light therefore proceeds to E instead of to M,

where it would go if the sun had no effect upon it. We see objects by the light which comes from them to our eyes. Our judgment of the position of an object must of necessity always be based on the direction of the rays of light within the eye itself. The far distant curvature of the starlight at the sun cannot therefore in any degree influence our sense of direction. The star, a, accordingly will appear to be at A in the direction of the straight line ELA; that is, it will apparently be displaced outward from the sun.

Since a photograph taken in the absence of the sun would show the stars in their true positions, a, b, and c, and another taken during the eclipse would show them in the displaced positions, A, B, and C, exact measurements of the distances aA, bB, and cC could be made by placing one photograph over the other. When this was done it was found that the stars were apparently displaced to nearly the exact amount predicted by Einstein. It is also to be noted that the closer the ray of starlight to the solar surface, the greater will be the deflection. Therefore the nearer the star

apparently is to the sun the greater will be its outward displacement.

The distances between the star-images are excessively small, amounting only to about two one-hundredths of a millimetre (0.02 mm.), or less than one one-thousandth of an inch (0.001 inch). On one plate the greatest distance was one fifteen-hundredth of an inch. Such a displacement as this, while quite measurable, would easily pass unnoticed unless there was some strong reason for suspecting its existence.

It seems not a little remarkable that the trivial apparent displacements of a few stars during an eclipse would attract the least attention from an exhausted world just emerging from the gigantic struggles of a universal war. The interest, in reality, was not in the displacements themselves but in the profound reasons for their occurrence, which involved not merely a new theory of the relation of gravitation to light, but the most profound revolution in the conception of the constitution of the universe that has ever occurred in the history of scientific achievement.

Leaving for the present the question of the bending of the rays of light, we may proceed to review briefly the various conceptions of the structure and order of the universe which have been held in different ages. In this manner we shall be able to see more clearly the position occupied by the theory of relativity in reference to the solution of the most magnificent problem which the natural universe presents.

THEORIES OF THE SOLAR SYSTEM

As long ago as the middle of the sixth century before our era, the early Greek philosopher, Pythagoras (570-504 B.C.), held the belief that the sun was the centre of the solar system and that the earth was a sphere freely poised in space. His disciples, if not Pythagoras himself, in addition to this heliocentric or sun-centre theory, also believed that the earth rotated on its own axis, producing in this manner the alternation of night and day. "According to some accounts Pythagoras had even raised his views so far as to speculate on the attraction of the sun as the bond of its union

with the earth." It seems probable, therefore, that in the acute mind of this ancient philiosopher the idea of gravitation first dawned upon the world.

Some writers claim that the doctrine of the sphericity of the earth was one of the great discoveries of Pythagoras. It was explicitly taught by Aristotle (384-322 B.C.), who supported the idea by the chief arguments still employed in modern textbooks of astronomy. At a somewhat later date a more complete heliocentric theory was developed by Aristarchus (280 B.C.); it had the great misfortune to receive the disapproval of his contemporary, Archimedes (287-212 B.C.), whose authority, as the greatest and most influential scientist of antiquity, on such a matter was supreme. The doctrines of Pythagoras, however, beyond all reasonable doubt were acquired by him during his travels in Egypt and Chaldea, where, it is now known, astronomical science was highly developed at a far remote age. Even in the eighth century B.C. most of the large cities in the valley of the Euphrates maintained observatories from which regular reports were sent by professional

astronomers to the king of Assyria. Many of the fanciful figures or constellations, in which the stars are grouped to this day, are known to have originated in Chaldea more than four thousand years ago, and they were widely recognized when Abraham left his ancestral home in Ur of the Chaldees to found a new nation and era.

As the heliocentric ideas proved uncongenial to the Grecian mind, the doctrines of Pythagoras passed over to the more receptive Italian schools of philosophy, whose exclusive property for a long time they remained. The essential features of the theory persisted in Italy to the time of Copernicus, who definitely acknowledges his indebtedness to Pythagorean ideas in developing his own system of the world, an indebtedness that is supported by the reference of Galileo himself, the most conspicuous advocate of the Copernican views, to "the Pythagorean opinion of the motion of the earth."

But the mind seems never to be satisfied with a theory until it has fully explored the opposing view. To regard the earth as the centre of the system was the natural alternative to the heliocentric

supposition. It was an idea, too, which made an unusually strong appeal to Greek philosophy.

The geocentric or earth-centre theory of the solar system, which is a purely Greek conception, seems to have resulted in part from the mathematical researches of Eudoxus, about 400 B.C., or, as is alleged by some writers, from a misunderstanding of them, and in part from the fanciful idea of Pythagoras himself of crystal spheres acting as the vehicles of the heavenly bodies, whose motions excited ethereal harmonies—the music of the spheres—which he alone of mortals was spiritually attuned to hear. As the weight of evidence, or at least of opinion, favoured the geocentric conception, the ideas which had long been accumulating were welded together about 130 B.C. into a consistent theory by Hipparchus, and later, about A.D. 130, by Ptolemy of Alexandria, the two ancient astronomers of unchallenged pre-eminence. Their choice, possibly not wholly without advantage as it is now viewed from the standpoint of relativity, determined the future development, or perhaps it

would be more accurate to say the sterility, of astronomy through the succeeding fourteen centuries of mediæval history.

The system of Hipparchus and Ptolemy, or the Ptolemaic system as it came to be termed, in its simplest form assumed the earth to be the centre of the solar system, while the sun, moon, and the five planets then known were placed in an onion-like succession of seven perfectly transparent and invisible solid spherical shells concentric with the earth, round which they revolved, carrying the heavenly bodies with them (Fig. 3). Beyond these were the fixed stars embedded in a single sphere called the primum mobile or the "first mover," which, in some unknown manner, not only maintained itself in motion, but supplied the motive power to revolve the whole celestial structure.

"The Ptolemaic system was in a geometrical sense defensible; it harmonized fairly well with appearances, and physical reasonings had not then been extended to the heavens. To the ignorant it was commended by its conformity to crude common sense; to the learned by the wealth of

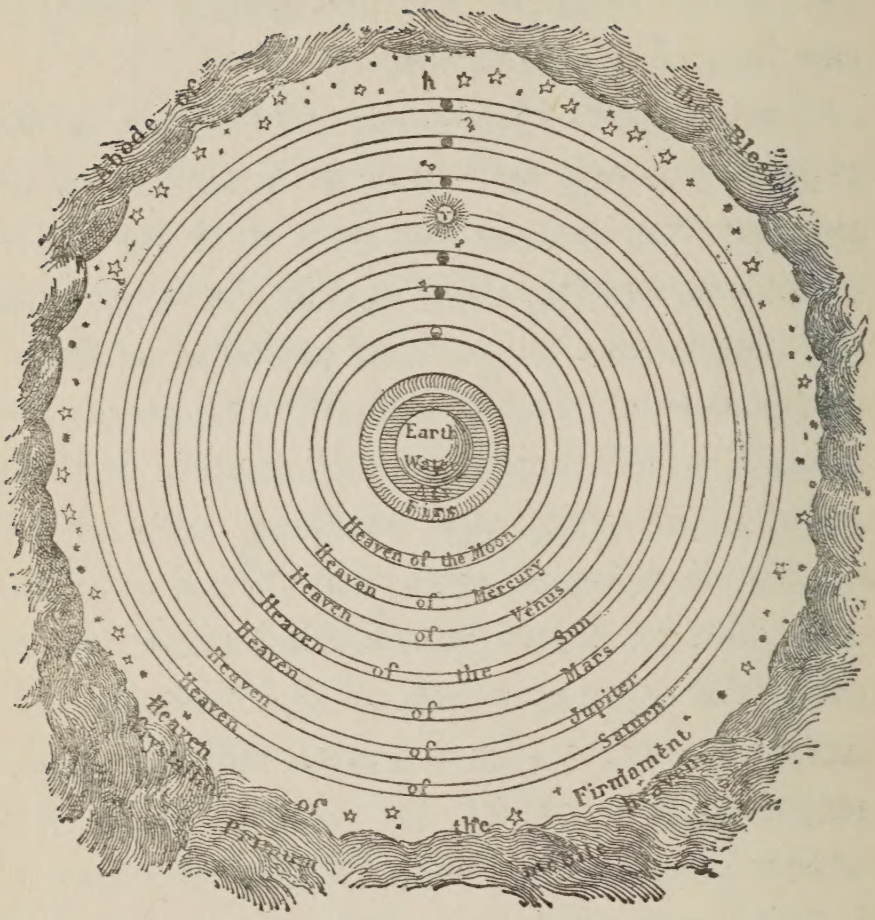

Fig. 3. Diagram of the Ptolemaic system. The four substances, earth, water, air, fire, which the ancients supposed to be the world elements, are at the centre.

ingenuity expended in bringing it to perfection."

It should be remarked that Ptolemy himself regarded the crystal spheres as convenient geometrical fictions. He was powerless to prevent his grossly unimaginative followers from insisting upon material structures.

Ptolemy was the last of the great ancient astronomers. For fourteen centuries "he had no successors—only commentators." The world of culture and learning, including notably, in that age, the ecclesiastical authorities, universally adopted his views. So prominent a part at a later period did the Papacy play in the defence of the geocentric theory that popular belief usually but erroneously ascribes its inception and establishment to the Church.

Under the impulse of the intellectual awakening of the Renaissance, the Ptolemaic astronomy and later the physical theories of Aristotle were subjected, especially in Italy, to intense criticism by many minds. The chief of these, in astronomy, was the great Nicolaus Koppernigk, or Copernicus as he is usually called (1473-1543), a canon

of the Church, probably of Polish parentage, but of Italian training in mathematics. In physics the outstanding figure was Galileo, "The Restorer of Reason in Italy," as Voltaire eulogistically styles him.

Copernicus, who on the day of his death received, but on account of blindness could only touch, the first published copy of his great book on the *Revolutions of the Celestial Worlds*, reconstructed the whole system of astronomy on the original heliocentric basis but founded his reasoning on the principle of the relativity of motion. The force of this statement will be realized when it is remembered that the farther the planets are from the sun, the slower are their motions. As the earth is the third of the planets in the order of their distances from the sun, the two inner or inferior planets, Mercury and Venus, will move faster, and the five or, including Pluto, the planet recently discovered from the brilliant mathematical predictions of the American astronomer Lowell, the six outer or superior planets will travel slower than the earth. There will be times,

therefore, when these planets will appear to earth-observers to move forward, to remain stationary, or to have a backward or retrograde motion. The apparent motions will be still more complicated since they are observed from the earth, which also has an orbital motion of its own. Using a modern illustration, the effect will be somewhat like the apparent motions of automobiles viewed by an observer in a street car, according as it is moving slower, at the same rate, or faster than the automobiles. These curious changes in the motions of the planets were naturally most puzzling to the early astronomers, and so they remained until they were clarified by the heliocentric theory.

Most unfortunately Copernicus retained some of the metaphysical ideas of ancient philosophy. Since, according to the teaching of Aristotle, nature was perfect and the circle was the only perfect curve, it was held that all motions must be described in circular orbits. This belief persisted with tremendously obstructive force until Kepler, after years of baffled efforts, finally freed himself and scientific thought from its pernicious influence.

Kepler himself remarks: "My first error was, that the path of a planet is a perfect circle;—an opinion which was a more mischievous thief of my time, in proportion as it was supported by the authority of all philosophers, and apparently agreeable to metaphysics." So firmly established had the venerable Ptolemaic theory become through the ever-deepening conservatism of many unquestioning generations that it was finally identified with theological orthodoxy, and even among men of science the new system of the heavens and of the earth, while admired as a daring speculation, only slowly became accepted as the truth. "At last Reason, and the Voyage of Christopher Columbus," says Voltaire, "restored to the Earth its ancient spherical Form, which the Egyptians and Chaldeans had given it."

As a unique illustration of the earliest reception of the Copernican system in England, while the Ptolemaic cosmogony was universally held, we may quote from a book entitled *Prognostication Everlasting*, written originally in the year 1555 by Leonard Digges, in which is to be found : "*A*

Perfit Description of the Coelestiall Orbes according to the most ancient doctrine of the Pythagoreans: lately revived by Copernicus and by Geometrical Demonstrations approved." "But in this our age," he remarks, "one rare witte, Copernicus, (seeing the continuall errors that from time to time more and more continually have been discovered, besides the infinite absurdities in their Theoretics, which they have been forced to admit that would not confesse any Mobilitie in the ball of the Earth) hath by long studye, paynfull practise, and rare invention, delivered a new Theoretick or Model of the world, showing that the Earth resteth not in the Center of the whole world or globe of elements, which encircled and enclosed in the Moone's orbe, and together with the whole globe of Mortalitye is carried yearely round about the Sunne, which like a king in the middest of all, raygneth and giveth lawes of motion to all the rest,sphaerically dispersing his glorious beames of light through all this sacred coelestiall Temple. And the Earth itselfe to be one of the Planets, having his peculiar and strange courses, turning

every 24 hours rounde upon his owne center, whereby the Sunne and great globe of fixed Starres seem to sway about and turne, albeit indeed they remain fixed—So many ways is the sense of mortal man abused."

Without careful and continuous observations, further progress in astronomy was impossible. To this task Tycho Brahe (1546-1601), a wealthy Danish nobleman, devoted his life. With odd-looking instruments of his own contrivance (Fig 4), but measuring accurately to ten seconds of arc, though the telescope had not then been invented, Brahe attained a higher degree of precision in his extensive observations of the positions of the planets than any of his predecessors and thus prepared material for the use of his illustrious successor.

The measurements were at once applied to the purpose for which they were prepared. Brahe's great friend and pupil, Kepler (1571-1630), the "legislator of the heavens," as he has been called, assumed the immensely laborious task of determining the type of planetary orbit

that would fit the observations with precision. With astonishing perseverance and resourceful-

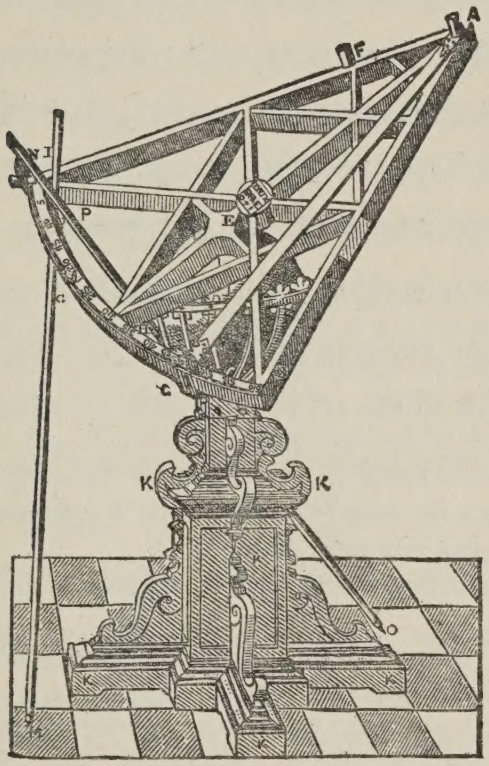

Fig. 4. Type of instrument designed by Brahe before the telescope had been invented. With the observations made by such instruments, Kepler laid the foundations of modern astronomy.

ness in the face of overwhelming discouragements, both intellectual and economic, for more than six years of incessant calculations, he tried circles and

combinations of circles, in accordance with Aristotle's ideas, but to no avail. Working with the orbit of Mars, he then tried an oval curve, only to find that the calculated and observed positions of the planet differed by eight minutes of arc.[1] Trifling as was this difference in measurement it nevertheless was fatal to his theory. Undaunted

[1] The circumference of a circle is divided into 360 equal arcs or degrees. A degree is subdivided into 60 minutes of arc, and a minute is further subdivided into 60 seconds, originally called second minutes, of arc. To distinguish them from minutes and seconds of time, the subdivisions of a degree are termed minutes of arc and seconds of arc. Some idea of the magnitudes of these quantities may be obtained from a few comparisons. To an observer situated *one mile distant:*

An object 92 feet wide has an angular width of 1 degree, written 1°.

An object about 1½ feet wide has an angular width of 1 minute of arc, written 1′.

An object about 3/10 inch wide has an angular width of 1 second of arc, written 1″.

One second of arc is about the angular width of a match seen at a distance of 600 yards. From the earth, the moon, which has a diameter of 2,160 miles and a distance of 240,000 miles, has an angular width of 30 minutes of arc. This also is the angular width of the sun, which is 92,870,000 miles distant and has a diameter of 867,000 miles. A magnitude of eight minutes of arc is about one quarter of the angular width of the moon.

In Kepler's problem the distance between the real position of Mars in the sky as *observed* by Brahe and the position it should have occupied as *calculated* by Kepler was one quarter of the diameter of the moon as it appears to us.

by his unsuccessful calculations, Kepler recommenced his work, declaring that with those eight minutes he would yet find out the law of the universe. His labours, brilliantly and immortally successful, were crystallized in three laws, forever to be associated with his name, which describe the order and prove the unity of the solar system.

As the first and second of Kepler's laws deal with the form of planetary orbits, only the first need be cited here. It states that "the planets revolve round the sun in elliptical orbits, with the sun in one focus" (Fig. 5).

There still remained to be discovered the relation of the length of the year, or the time of revolution of a planet, to its distance from the sun. By degrees the solution of this basic problem, which had occupied most of his active life, was achieved, and he formulated his discovery in his third law, which states that "the squares of the periodic times of the planets are to each other as the cubes of their mean distances from the sun." This law may be expressed in various ways. One simple form is that the speed of each planet in its

orbit is inversely as the square root of its distance from the sun. If one planet is four times as far from the sun as another, the first has only one half the

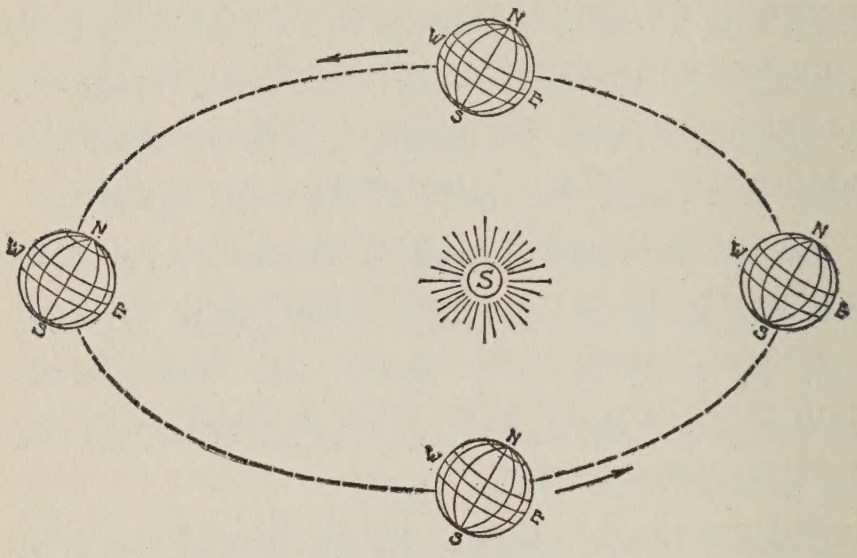

Fig. 5. Diagram of the elliptic orbit of the earth with the sun, S, in one of its two foci. The inclination of its polar axis, NS, on account of the spinning motion of the earth, always keeps in parallel directions.

speed of the second. Still another expression of the law is that the product of the distance from the sun and the square of the speed is the same for each planet.

"Of all the laws," says the astronomer Herschell, "to which induction from pure observation

has ever conducted man, this third law of Kepler may be justly regarded as the most remarkable, and the most pregnant with important consequences." Two of these conclusions are: first, that it must be the same force which operates upon all the planets; and second, that this force acts independently of the kinds or states of matter of which the planets are composed. The law therefore asserts the organic unity of the solar system.

The exultation of the ardent spirit of Kepler upon the discovery of this law found expression in extravagant form: "It is not eighteen months since I got the first glimpse of light, three months since the dawn, very few days since the unveiled sun, most admirable to gaze upon, burst upon me. Nothing holds me; I will indulge my sacred fury; I will triumph over mankind by the honest confession that I have stolen the golden vases of the Egyptians to build up a tabernacle for my God far away from the confines of Egypt. If you forgive me, I rejoice; if you are angry, I can bear it; the die is cast, the book is written, to be read either now or by posterity, I care not which; it may well

wait a century for a reader, as God has waited six thousand years for an observer."

In his laws Kepler described the orbits of the planets, but he had no proper conception of forces. He was therefore unable to suggest the cause of the ellipticity of the orbits which he had discovered, and of the curious relation between their periods of revolution and solar distances. Hence he could not arrive at the full significance of his far-reaching achievement. "The Extreme Sagacity of Kepler," remarks Voltaire, "discovered the Effect of which the Genius of Newton has found out the Cause." If Newton, however, had not had at his command the system of Copernicus and the laws of Kepler, his still profounder discoveries might have been reserved for the glory of some later man of science.

The chaotic views of the causes of celestial motions characteristic of the pre-Newtonian astronomers are well illustrated by the reasons advanced by Kepler himself to explain his Third Law. To quote Voltaire again: "Kepler, who found this Proportion [Law], was very far from

finding the Reason for it. Being less a good Philosopher than an admirable Astronomer, he says that the Sun hath a Soul ; not an intelligent Soul, Animum; but a vegetant, active Soul, Animam: That in turning round upon his own Axis, he draws the planets to himself; but that the Planets do not fall on the Sun, because they also revolve upon their Axes. In making this Revolution, says he, they present to the Sun sometimes a friendly, and sometimes a hostile side; the friendly side is drawn, and the hostile side is repell'd; which produces the annual Courses of the Planets in the Ellipses."

"It must be confessed," continues Voltaire, "for the Humiliation of Philosophy, that it was from this Reasoning, so very unphilosophical, that he concluded the necessity of the Sun's turning round on its Axis. Error accidentally conducted him to Truth; He conjectured the Rotation of the Sun above 15 Years before the Eyes of Galileo discovered it by the Help of Telescopes."

Parallel with the discoveries of Kepler were those of the great contemporary Italian natural

philosopher, "the starry Galileo" (1564-1642,) the founder of modern physics, whose experiments on falling bodies at the leaning tower of Pisa brought to an inglorious yet dramatic close the venerable, repressive, and long authoritative physics of Aristotle, by the substitution of experiment for conjecture. Aristotle had taught that it was reasonable to suppose a heavy body would fall to the earth proportionately faster than a lighter. For two thousand years, apparently, it had occurred to no one to question this assumption or to test it by experiment. Taking advantage of the inclination of the tower, Galileo, in the presence of the whole University of Pisa, let fall simultaneously heavy and light bodies, which were observed to strike the ground at the same instant. This experiment marks the beginning of modern inductive or experimental science. The simplicity of the method, combined with the incontrovertible nature of its evidence, swept it victoriously over the most determined opposition of his age and established it as the accepted mode of investigation of the phenomena of nature.

To Galileo the world is also indebted for the discovery of the pendulum, which shortly afterward was utilized by the Dutch scientist Huygens in his admirable invention of the clock. To the same Italian philosopher is due the discovery of the telescope in 1609, which has provided astronomers with instruments of marvellous precision, and, greatest of all from the standpoint of theoretical importance, the explanation, in part, of accelerated or changing motions by which, as Newton afterward showed, the forces which produce them may be measured.

Though Galileo had excellent ideas of force and its consequence in accelerated motion, he failed to realize the significance of Kepler's laws of planetary orbits. "The two lines of inquiry accordingly remained apart till Newton made them coalesce in his gravitational system."

The transition from the solid crystalline spheres of the Ptolemaic system to the almost empty universe of Newton was not attained by a single leap of the imagination. Between the two lay the vortex theory of space conceived by the French

philosopher, Descartes (1596-1650), a younger contemporary of Galileo. According to this "bold and yet plausible" hypothesis the universe was assumed to be everywhere full of matter, which had been created in the form of cubes, but through ages of grinding together had become reduced to globules and fine dust. In a completely full universe no single particle can move without causing motion of all the rest. Thus vortices or whirlpools (Fig. 6) were produced, into whose quiet centres the fine cosmic dust collected and formed stars and suns. Other matter of a coarser type aggregated into planets on the rims of the vortices which carried them around the central sun by their whirling motion. Matter dispersed throughout the universe in still a third degree of fineness provided a means by which actions were transmitted, such as a pressure exerted by the moon upon the earth, by which ocean tides were supposed to be produced. The pressure or impulsion forced the water away from the region of application, thus causing the low tide. In the hands of its author the theory of vortices was used

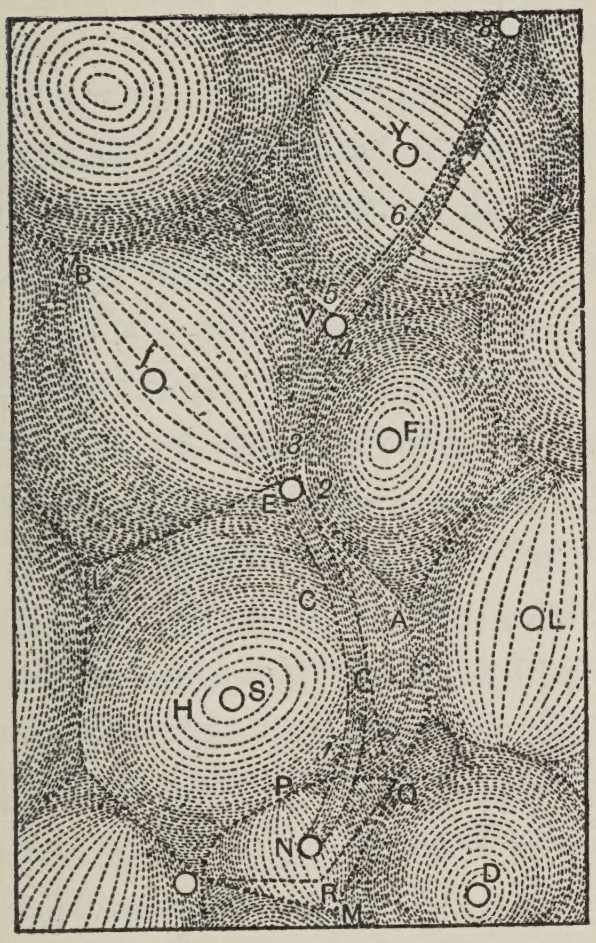

Fig. 6. Diagram of the universe as imagined by Descartes. D, S, and F are centres of vortices. L, f, and Y are regions of force action between the vortices.

to explain not only gravity, but also the phenomena of heat, magnetism, light, chemistry, and even of biology as well.

The theory of Descartes was as great an advance over the hypothesis of Ptolemy as the ether theory of Newton was over that of Descartes. From the time of its inception, in 1644, for a period of almost a century, the vortex theory received strong support from distinguished philosophers and mathematicians on the continent of Europe, while in the universities of England its authority for a long time was undisputed. In this system of astronomy Newton himself received his early training. "It was a grand hypothesis to account for the movements of the Universe by mechanical processes. It ended the Aristotelian physical distinction between matter beneath the moon and that in starry spaces beyond. It banished spirits and genii which even Kepler assumed as the guardians of planetary movements."

The stage was now prepared for the advent of Newton (1642-1727). In the same year in which the aged, blind, and persecuted Galileo

died, was born on Christmas Day the master mind of the race. His comprehensive and penetrating intellect formulated in three fundamental laws the properties of uniform and of accelerated motions with their relation to the conception of force which he introduced. As these laws are not required for the present purpose they are not quoted here. Newton also established the celebrated law of gravitation which bears his name. This law states that "every particle of matter in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres." Thus, if two bodies are moved two or three times as far apart the attraction between them becomes only one quarter or one-ninth of its first value.[1]

[1] In symbols the law of gravitation is stated :

$$F = k\frac{m\,m'}{d^2}$$

where F is the force, m and m′ are the masses of the particles, d is the distance between them, and k is a constant representing the force of attraction between two one-pound balls when their centres are one foot apart. It is equal to about 0.000 000 000 033 of a pound weight.

Though Newton's theory neither required nor admitted forces of repulsion and, of course, brushed aside the personal "friendly" and "hostile" aspects of inanimate bodies, it must be admitted that it was equally powerless with Kepler's absurd idea to explain the nature of the gravitational force he assumed to exist.

Kepler's laws relating to the elliptical orbits of planets and to the variation of their speed with distance were proved by Newton to be three of the many consequences of the operation of the law of gravitation. Upon the far-reaching conception of a central gravitational force acting between the sun and planets he completed the establishment of the Copernican system, which until then had presented a grand series of motions of the planets without forces to control them. While the scheme of Copernicus referred only to the solar and planetary world, the gravitational system of Newton embraced the universe. In his masterly treatise, the famous *Principia* or "The Mathematical Principles of Natural Philosophy," Newton set forth a detailed system of physics

and astronomy which by its completeness and accuracy has remained unto the present time, and will ever continue to stand, not only as a colossal monument of his genius, but as the first and simplest approximation to the facts.

The differences between the Cartesian and Newtonian systems were happily summarized by Voltaire: "A Frenchman who arrives in London, finds a great alteration in philosophy as in other things. He left the world full, he finds it empty. At Paris you see the universe composed of vortices of subtile matter, in London we see nothing of the kind. With you it is the pressure of the moon which causes the tides of the sea, in England it is the sea which gravitates towards the moon; so that when you think the moon ought to give us high water, these gentlemen believe that you ought to have low water; which unfortunately we cannot test by experience; for in order to do that, we should have examined the moon and tides at the moment of the creation. You will observe that the sun, which in France has nothing to do with the business, here comes in for a quarter of it. Among

you Cartesians, all is done by an impulsion which one does not well understand; with the Newtonians, it is done by an attraction of which we know the cause no better. At Paris you fancy the earth shaped like a melon, at London it is flattened on the two sides [poles]."

In addition to his other achievements Newton also solved the age-long problem of the origin of colours by proving that white light is simply a mixture of colours which when separated from each other by prisms of glass or by drops of water form the spectrum or rainbow. He propounded also a corpuscular theory of light, that is, a hypothesis that light consisted of particles, which harmonized with such facts as were known sufficiently well to maintain its existence for a hundred years. Although it has been discarded for the last century, according to the most recent developments in optics it is now unexpectedly proving, instead of an absurdity, an important part of the truth. As a consequence of his theory of light Newton deduced an attractive effect upon it by the force of gravity. Had he applied his laws to rays of

starlight passing near the sun, Newton would also have discovered their deflection, but only of one half the amount that Einstein predicted. To this fact we shall allude later.

To subsequent as well as to contemporary astronomers it appeared conclusive that Newton had placed the laws governing the universe upon foundations that could never be moved. Herschell, writing in 1830, completed his appreciation of the Newtonian philosophy by declaring that "the efforts of a single mind sufficed for the establishment of the system of the universe on a basis never to be shaken." The French mathematician Lagrange, himself a man of magnificent intellectual power, wrote: "Newton was the greatest genius that ever existed, and the most fortunate, for we cannot find more than once a system of the world to establish." Whewell, the English historian of the inductive sciences, said that the law of gravitation "is indisputably and incomparably the greatest scientific discovery ever made, whether we look at the advance which it involved, the extent of truth disclosed, or the fundamental

and satisfactory nature of this truth." Pope's couplet placed in the room in the house at Woolsthorpe where Newton was born expressed the sentiment of his own as well as that of the succeeding age:

"Nature and Nature's laws lay hid in night;
God said, Let Newton be! and all was light."

The unbounded admiration of Voltaire found expression in poetic language:

"God speaks, and Chaos at his Voice subsides;
In various Orbs the mighty Mass divides:
At once they gravitate, they strive to fall,
One Centre seeking, which attracts them all.
That Soul of Nature, that all-moving Spring,
Lay long conceal'd, an unregarded Thing;
'Til Newton's Compass, moving thro' the Space
Measures all matter, all discover'd Place;
Finds Motion's Cause, Philosophy unleavens,
Lifts up the Veil, and open'd are the Heavens."

The sway of Newton over the empire of physical and astronomical science was complete and undisputed. For two centuries he has had "no successors, only commentators." To our generation has been accorded the high privilege of

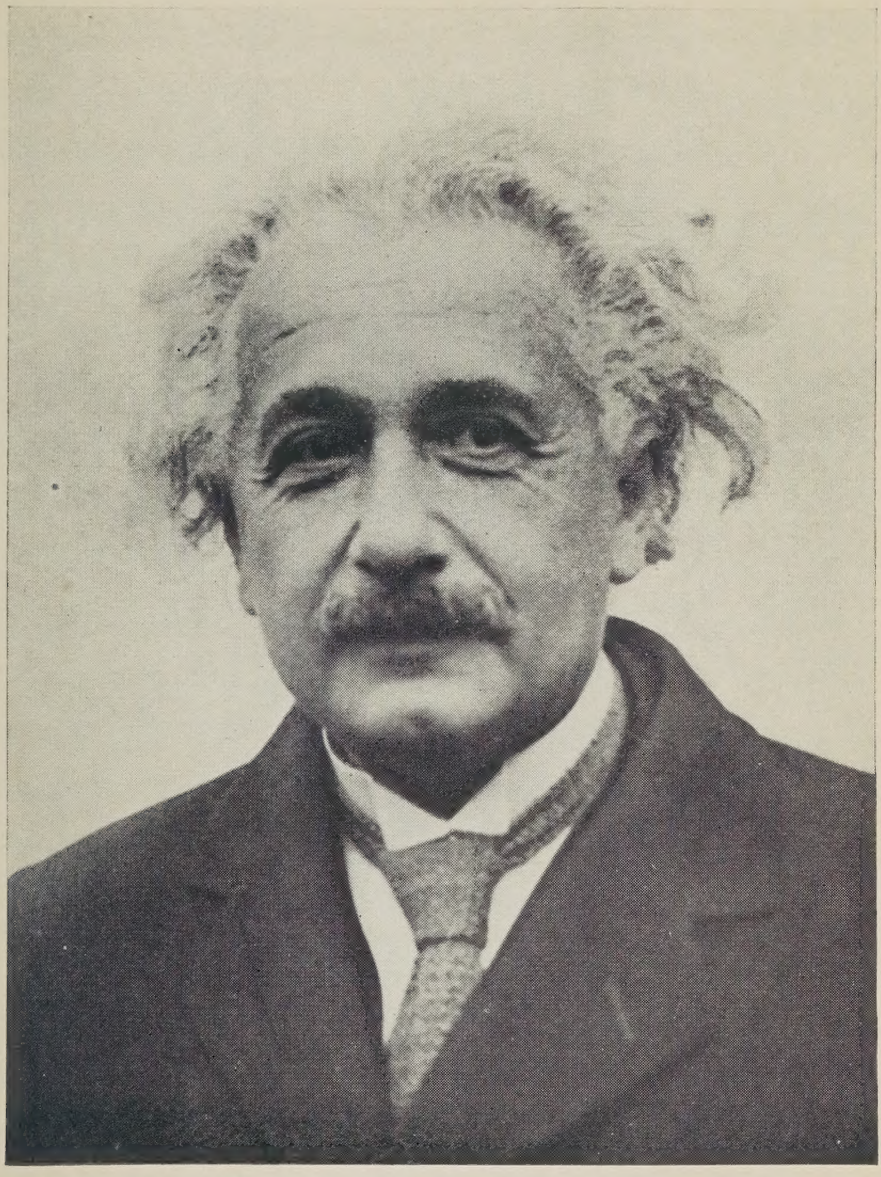

Fig. 7. Einstein *To face page* 38

acclaiming a regal successor to the sovereignty of Newton in the person of Albert Einstein and a new conception of the universe in his theory of relativity (Fig 7).

The men who have most conspicuously contributed to the world-systems of Pythagoras, Ptolemy, Copernicus, Newton, and Einstein are placed diagrammatically in Fig. 8 in four converging groups. By this arrangement the time and effectiveness of their influence may quite accurately be indicated. From this diagram we also see that the ideas of great thinkers, while developed independently of each other, are in reality only parts of a larger plan. Of the fundamental connection between their contributions to knowledge the individuals themselves had no conception.

The underlying relationship of the great concepts of science conceived independently of each other need occasion no surprise. There is but one universe, and any fundamental principle discovered in any age must possess some relation to every other principle of the world, however remote from each other they may at any time appear to be, since

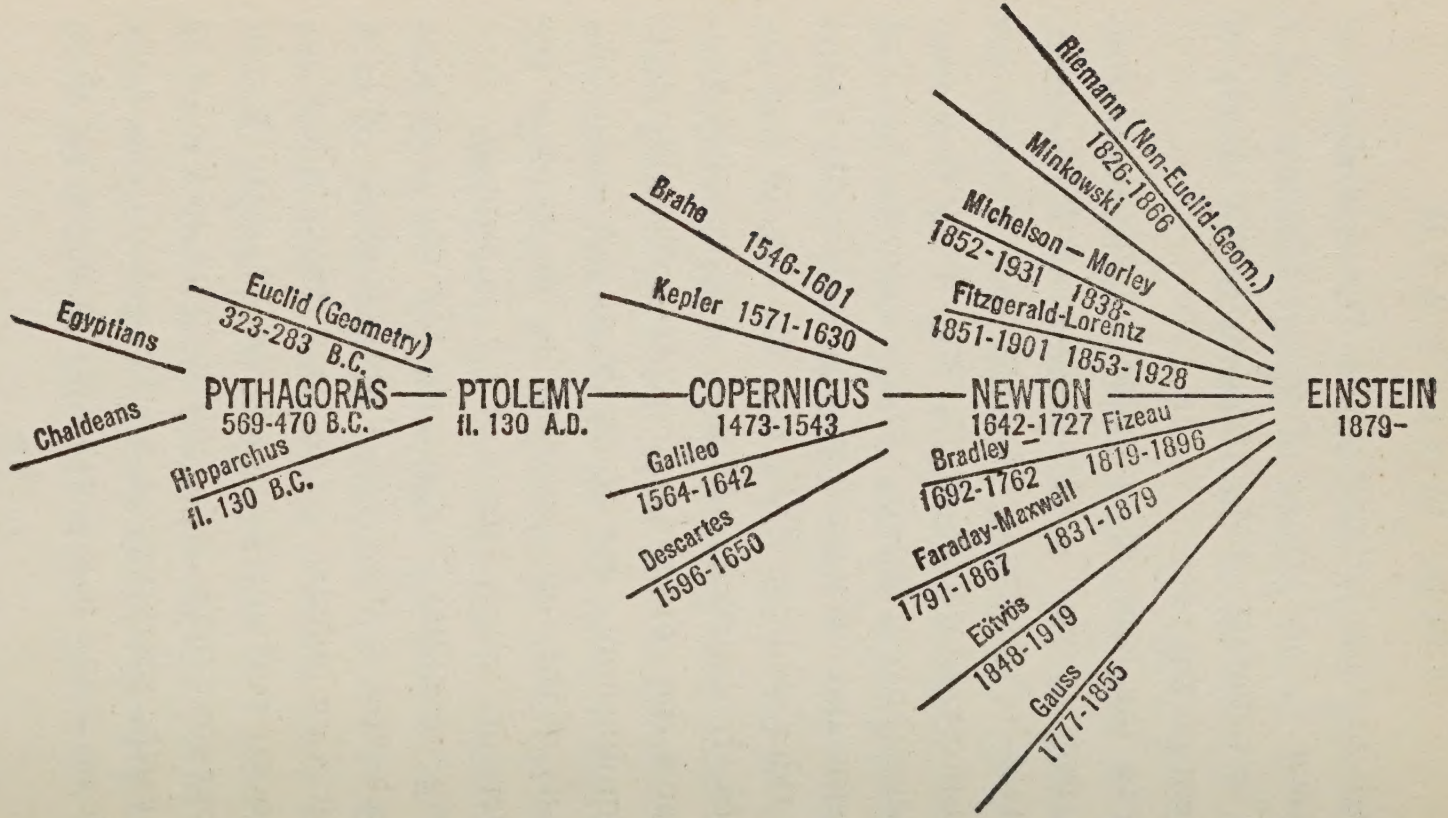

Fig. 8. Diagram showing the development of theories of the universe from Pythagoras to Einstein.

each is necessarily but a partial aspect of the same universe.

The culmination of ages of investigation of the system of the planets is the discovery of gravitation as the fundamental force of nature. Upon this great principle of attraction the unrivalled interest in physics and astronomy centres. This omnipresent force holds the earth together against the disruptive tendencies of its own rotation, keeps the seas and rivers in their basins, lifts the waters into tides, and constitutes the driving force of the waves. It depresses the floors of the oceans; it elevates the continents and preserves the whole in equilibrium. Gravitation limits the height and density of the atmosphere and confers upon it the power of transmitting sound vibrations, thus giving mankind the means of intercourse by speech and a basis for the pleasureable art of music. Combined with heat, it establishes the winds and ocean currents, distributes water in the form of vapour over the land, draws the rain and snow to the earth, gives power to the waterfall. To the same force is due the stability of the car, the ship,

the submarine, the aeroplane, thus rendering possible transportation by land and the navigation of the sea and air. It gives structures firmness and strength, the foundations of the art of architecture. With gentle motion it draws a leaf softly to the ground, it shatters a city with violence into ruins. By gravitation man preserves his upright posture, which gives dignity to his stature, colours his outlook upon the world, and determines the shape of his dwellings, the form of his tools, the manner of his occupations.

Gravitation moulds planets and suns into spheres; it gives permanence to their motions; it maintains unchangeable the length of the year; it establishes the cyclic recurrence of eclipses. It exercises its invisible sway within the narrow confines of the atom; its inescapable dominion includes the remotest stars. By this force atoms are united into worlds, planets into systems, stars into clusters, galaxies into a universe. In the strong imagery of Job, it "binds the sweet influences of Pleiades," it confirms "the bands of Orion," it "brings forth the constellations in their season,"

it "guides Arcturus with his sons." It stamps all nature with the insignia of unity.

The solution of the problem of gravitation has been attended with astonishing difficulty. It is inconceivable that the great but unknown men of Egypt and Chaldea, who laid the foundations of astronomy, should never have speculated upon the cause of the celestial motions they so accurately observed. But whatever may have been the nature of their ideas, no record of them has survived the ruin of their civilizations. It baffled detection by the subtle intellect of Greece. The powerful minds of Ptolemy, Copernicus, Galileo, Kepler, and Descartes wrestled with the problem in vain.

Ptolemy, having no knowledge of forces, was compelled to picture the universe as a mechanism of spheres. Copernicus abolished the idea of such a mechanism, but, likewise ignorant of forces, he left the system moving uncontrolled in space. Kepler imagined that in the sun resided a spirit which exerted a moving influence whose virtue weakened with the distances of the planets to which it extended. Though Descartes erroneously

accounted for the motions of the planets by assuming the universe to be completely full of whirlpools of matter, it was undoubtedly a great achievement to refer them to a type of mechanical circular motion which had the merit of being well known. Newton provided for the continuance of the motions, but not for their beginning, by a system of immaterial forces of attraction which were transmitted by the ether in space from one body to another.

On this point the language of Newton is very explicit: "That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance through a vacuum and without the mediation of anything else, by and through which this action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it." Einstein now disregards the ether as an unnecessary complication of the system. From the new standpoint of relativity, the force of gravitation is not wholly

confined to the action of matter ultimately upon matter. Part of its action is restricted to the production of some modification or distortion of the space surrounding the matter which exerts the force. In Newton's system, matter was the active agency and the ether a passive conveyer of force. In the new system, the activity resides chiefly in space, and matter is largely the passive respondent.

Matter not only exerts a gravitational force of its own; it also transmits nearly perfectly, perhaps even perfectly, the force which is exerted by other matter. So transparent to gravitation is the earth that, when it comes between the sun and moon, the force of attraction between these two bodies passes through the earth with a loss by absorption of less than one eight-hundredth of its value and possibly with no loss at all.

Though two hundred theories of the nature of gravitation have been devised, it still preserves inviolate the mystery of its origin and and the mode of its operation. The discovery of gravitation, probably the greatest of all scientific achievements, by Newton, together with the approximate

formulation of its law by him, solved to a high degree of perfection the problem of matter in relation to its motions. The more fundamental theory of gravitation discovered by Einstein blends matter and its motions with the properties of space and time and carries the solution of the enlarged problem to an immensely greater degree of precision.

THE ETHER

In the light of modern knowledge what are we to believe regarding the real nature of space? As the distance of the sun from the earth is nearly 93,000,000 miles, and of the stars from four light-years[1] to millions and even, it has been suggested, to one hundred and fifty millions of light-years, space itself must be, or contain, a medium of marvellous transparency which will transmit light through such vast unthinkable distances with little absorption. Gravitational force, in the Newtonian conception, extends at least from the sun

[1] A light-year is the distance light travels in a year at the rate of 186,300 miles per second. It amounts to 5,875,157,000,000 miles. Sometimes for convenience the velocity of light is taken as 186,000 miles per second.

to the outermost planet. It seems impossible to believe that an attraction can act upon bodies at such distances unless it acts continuously upon a transmitting medium extending without a break between them. Such considerations as these have led to the assumption of an ether uniformly diffused throughout space, a conception probably growing out of a refinement of Descartes' theory of a full universe. The properties of such an ethereal medium must necessarily be extraordinary. It must be frictionless, since the bodies of the solar system are not observably retarded by it in their motions, as is shown in the case of the earth by the invariable length of the day and of the year.

For the same reason it must be of vanishingly small density. It must possess perfect elasticity and a rigidity greater than that of steel in order to transmit radiation in wave form with the enormous speed of light. It must also be incompressible. For such reasons as these, the ether has been regarded as a solid with a continuous structure, rather than as a fluid.

Such a conception of the ether seems to involve

contradictory properties and in consequence to be highly absurd. To realize the distinction between solid and fluid substances requires some knowledge of the theory of the structure of matter. All material substances, whether solids, liquids, or gases, are composed of enormous numbers of excessively small particles which are called molecules. The molecules are composed of two or more smaller particles which are called atoms. The molecules are not continuous with each other, nor are they in contact. They are always separated by empty spaces in which they are continually in motion. In a fluid substance, whether it is a liquid or a gas, the molecules move about with great freedom: they possess no power of maintaining the body in any fixed shape. In a solid, on the contrary, the particles, while able to oscillate freely like a pendulum in their allotted spaces, keep permanently their relative positions. Thus the form of a solid body remains intact. If the ether is solid, its constituent parts when displaced can make only very slight temporary excusions away from their usual positions, to which they always

return. Since the ether offers no resistance it permits matter, whose molecules have relatively large spaces between them, to go through it. Wave-motion and force-actions are also freely transmitted. If, however, the ether is continuous in structure and incompressible, how can any particle even of infinitesimal size move without resistance or without compressing it? These contradictory conclusions are now avoided by the most recent conception of the atom, that the ultimate constituents of matter are not material particles at all, but consist of tiny permanent groups of still tinier waves in the ether or in space itself. To this idea allusion will later be made.

These properties of the ether, it will be noticed, are all mechanical or dynamical in character. This is but natural since the chief development of the ether concept occurred during the period when other forces than those of a mechanical type were but little known. An outstanding feature of the nineteenth century, however, was the enormous extension of knowledge of electricity and magnetism, due principally to the far-reaching experi-

mental discoveries of Faraday (1791-1867), "the prince of experimental philosophers," and later to their even more profound mathematical formulation by Maxwell (1831-1879). As the assumption of a second medium for the transmission of electric and magnetic forces could scarcely be tolerated, the properties of the single ether had to be enlarged to include the new functions also. Maxwell's theory that light waves, instead of being merely elastic ethereal vibrations like waves in water, were electro-magnetic in their nature, similar to the waves now employed in radio broadcasting, which is itself a result of the development of his theory, had by far the greatest influence in effecting a change in the ideas of the ether. The still more recent discovery, principally by Sir Joseph Thomson and Lord Rutherford, of the electrical constitution of matter, that is, that atoms are complex structures of excessively minute protons, or elementary charges of positive electricity, and electrons, or elementary charges of negative electricity, held together by electric attraction, has completed the evidence that the

world is fundamentally electrical rather than dynamical in its constitution. The standpoint from which we now view matter, ether, and space, therefore, has essentially altered since Newton's time. A new conception of the universe accordingly has become necessary, and this primarily is the reason for the theory of relativity.

THE UNIVERSALITY OF MOTION

The matter of the universe from stars to atoms is incessantly in motion. Newton perfectly realized this condition, but in order to satisfy the intellectual craving for some place of absolute rest he suggested that in the inaccessible regions beyond the stars the imagination at least might picture a state of unalterable repose. Since it was hopeless to find matter devoid of motion, a far less remote possibility was later entertained, that the ether itself may everywhere be completely immobile or at absolute rest. Such, therefore, has been the assumption.

The motions of bodies are measured entirely with reference to each other. A steamer, for

example, may be sailing across a river. The passengers may walk about its deck in every direction as if the steamer were at rest. But while they walk, the steamer itself has a motion from one bank toward the other. The river current also carries the steamer along with it. The river travels with the earth in its diurnal rotation round its axis and in its annual revolution round the sun. The sun and its family of planets are swiftly coursing in some farther orbit within the confines of the vast galactic—that is, the "milky way"—universe or spiral nebula of which our solar system forms, in respect of size, so insignificant a part. The galactic universe is probably executing some inconceivably vaster movement relative to the innumerable other "island universes" distributed at enormous distances throughout the far reaches of space.

Apparently the endless series of motions will never cease. All these motions may be specified relatively to each other, but nowhere can be found a body absolutely fixed in position, to which all motions can be referred.

For the purpose of giving precision to our ideas

the system of reference lines or co-ordinates devised by Descartes may advantageously be used. This consists of either two or three straight lines or axes, perpendicular to each other, as in Fig. 9,

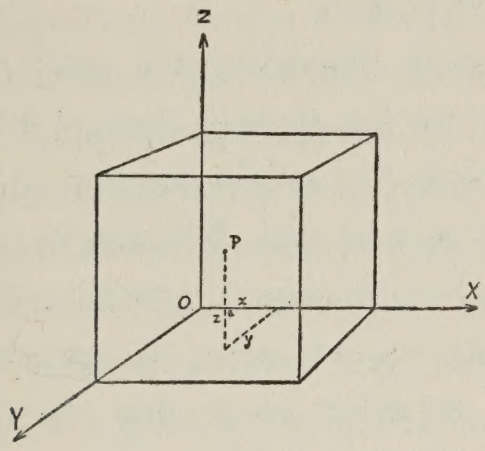

Fig. 9. Cartesian axes. The point of origin is O, from which all measurements are made along, or parallel to, the three axes OX, OY, OZ. The point p is located by measuring x, y, and z.

which meet at a single point called the point of origin or, briefly, the origin. In order to determine our position of relative rest or motion in a room, we may select one of its corners as an origin or fixed point from which to measure distances. Extending from this point there are three lines, where the floor and walls meet, at right angles

with each other, which may be designated axes, two of them on the horizontal plane of the floor, which may be termed the X and Y axes, and the third in the vertical direction, which may likewise be called the Z axis.

We can now determine the exact position of each person on the sloping floor of the room by measuring from the origin the proper number of feel parallel to each axis. Nor would such a position relative to these axes be altered in the slightest degree if some power were to remove the room a few feet or miles away after the manner of the magic palaces in Oriental tales. Again, we may refer our position to the nearest rectangular intersection of two streets. In such a case our position relative to that origin would be altered by the removal of the building. Should the whole city be removed the new origin would be transferred with it, and again we should have no relative change of position. Each set of axes we choose may be used in turn as a frame of reference. Finally, we may set the origin of a terrestrial frame of reference at the centre of the earth, or

the origin of a planetary frame of reference at the centre of the sun. In every case, it will be noticed that the motions are always relative in character. For the determination of absolute motions, a fixed point of origin and frame of reference must be provided. But an origin of this character cannot possibly be found in any matter. If, according to the assumption, the ether is at absolute rest, the measurement of our motion relative to it seems to be possible, thus determining our absolute velocity in space. If the ether itself is at rest, then matter, which is porous on account of its atomic structure, passes through the ether without disturbing it, as a sieve or wire net-work passes through air or water.

Since the attempted experimental solutions of this fundamental problem have led directly to the first principle of Einstein's theory of relativity, it is necessary to examine it in some detail. The first apparent indication of the absolute motion of the earth through space was obtained by the English astronomer Bradley (1692-1762), who observed that the stars seemed to describe yearly orbits,

those overhead, or in the zenith, being nearly circles, those on the horizon straight lines, while between the two extreme positions the orbits were ellipses. These orbits are exceedingly small, their greatest diameter amounting to only 40 seconds of arc. As the real motions of the stars, on account of their vast distances from the earth, can be detected in very few cases and then only with instruments of the utmost precision, which were unknown in Bradley's time, the slight wandering or aberration that Bradley observed to be repeated every year must be due to some other cause. After four years of consideration, the true explanation occurred to him, that the *apparent* motions of the stars were due to the *real* periodic motion of the earth in its orbit. Each tiny apparent orbit of a star is a diminutive representation of the real orbit of the earth, its shape varying according to the direction from which the earth's orbit might be viewed from the star.

The explanation of this effect, the aberration of light as it is called, is made easier by considering an analogous example. If, in a shower of rain

when drops are falling vertically, a person stands holding a long tube in his hand, a raindrop will pass through the tube without touching the sides only when it is held in a vertical position. Should the person now walk uniformly forward he will push the side of the vertical tube against the drop before it has time to pass through the tube. The only way to avoid this is to tilt the upper end of the tube forward to such an extent that, as the drop falls, the advancing tube will not touch it, as shown in Fig. 10. While the raindrop falls *vertically* from D to D_1, the tube must be moved *horizontally* to the position A_1 B_1. While the raindrop is reaching D_2 and D_3, the tube must be moved to A_2B_2 and A_3B_3. A little consideration will show that the faster the person walks, the greater must be the inclination of the tube to allow the falling drop to pass through freely. If we express the angle of inclination of the tube in mathematical form we shall find it to be measured in terms of the velocity of the tube, v, in the horizontal direction divided by the velocity of the raindrop, V, in the vertical direction. This is

usually expressed as $\frac{v}{V}$. If, for example, the drop fell unifromly at the rate of 30 feet per second

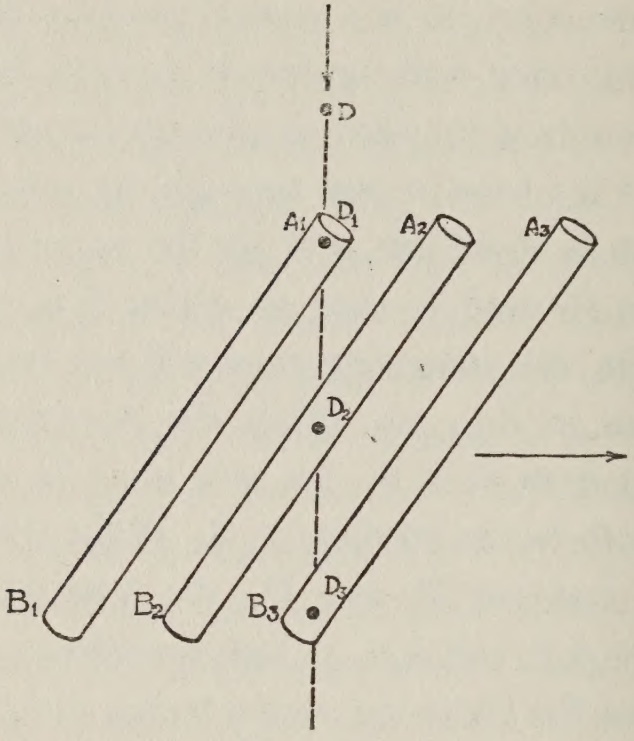

Fig. 10. Diagram illustrating the vertical fall of the raindrop D through the inclined tube AB, which is moving horizontally in the direction of the arrow.

and the man walked 5 feet per second, the ratio would be $\frac{v}{V} = \frac{5}{30} = \frac{1}{6}$, from which the angle of the inclination of the tube can be calculated. If we

measure this angle and the rate at which the man is walking, then the velocity of the raindrop can be computed.

If the star to be observed is situated directly overhead, the descending light waves correspond to the raindrop falling vertically. If the earth were at rest, the observing telescope would have to be placed in a vertical direction also, in order that the starlight might pass through the tube. Since the earth and telescope are travelling through space around the sun with a velocity of 18.6 miles per second, the telescope must be tilted or inclined slightly forward so that the light waves will not strike its sides. The angle of inclination of the telescope, or the aberration of light, is measured just as in the case of the falling raindrop by dividing the velocity, v, of the telescope, i.e. of the earth, by the velocity of light, which is usually denoted by the letter C. In this case

$$\frac{v}{C} = \frac{18.6 \text{ miles}}{186{,}000 \text{ miles}} = \frac{1}{10{,}000}.$$

This effect was originally used by Bradley to compute the velocity of light, which could be

done by measuring the angle of inclination of the telescope, since the velocity of the earth in its orbit is known. In explaining Bradley's experiment it is assumed that the ether is absolutely at rest while the telescope and the air inside it alone are in motion.

THE ATTEMPT TO MEASURE THE ABSOLUTE VELOCITY OF THE EARTH

Many attempts have been made to detect and measure the absolute motion of the earth through the fixed ether. The most direct and conclusive of these is the method devised by the American scientists, Michelson and Morley, in 1881, the former of whom was until lately engaged in physical research (Fig. 11). Since the polar axis of the earth, while moving in its orbit, always occupies parallel positions, as a reference to Fig. 5 shows, the orbital velocity of 18.6 miles per second takes place from west to east, and there is no velocity in the north-south direction. As one writer expresses it, Michelson and Morley timed a race between two rays of light in these two

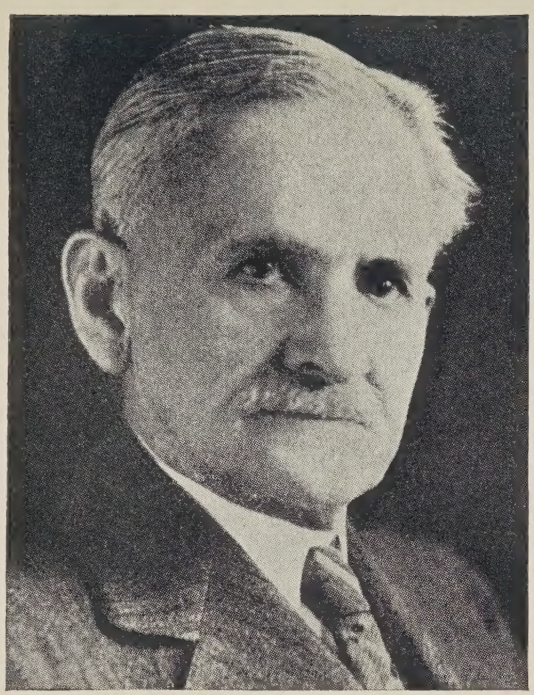

Fig. 11. Michelson

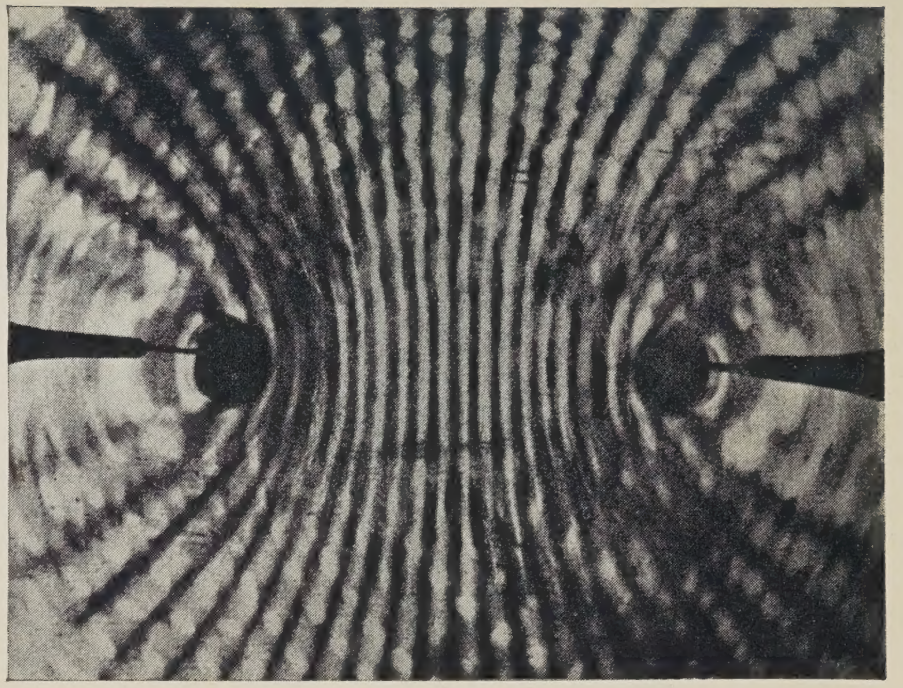

Fig. 12. Interference Bands

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A. A. Michelson *Studies in Optics* (1927).

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directions in order to discover which would win. This experiment may first be described by an analogy. Suppose a square frame LMNP (Fig 13), whose sides are capable of sliding over each other,

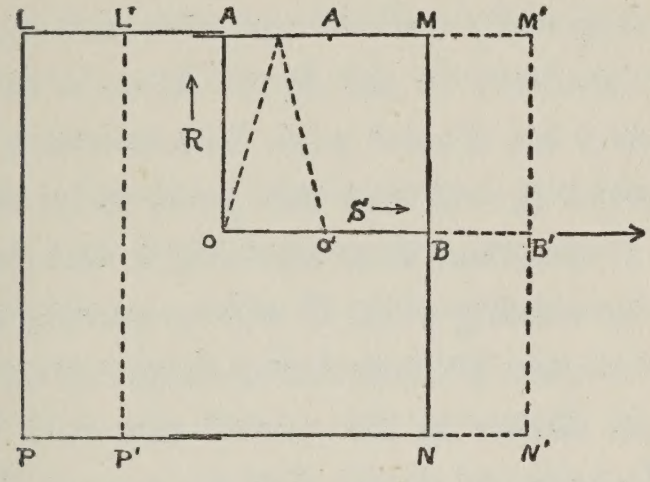

Fig. 13. The Michelson-Morley experiment. Diagram to illustrate the paths of the runners, R and S, as the square frame LMNP moves toward the new position L'M'N'P' while they are running.

is placed on a floor, and two runners, R and S, of exactly equal speed start at the same instant from the centre O of the square, one of them, R, toward A, and the other, S, toward B. Since the frame is square, OA is equal to OB, and both runners will reach their destinations and return to O in exactly the same time. Now while the

runners are moving let the frame also be moved uniformly in the direction OB, indicated by the arrow. Since the first point A moves steadily forward, the runner R, from O to A will have to move diagonally upward and then downward to O, as indicated by the dotted lines, in order to travel over his allotted path. The runner S, moving toward B, will find that point to be moving ahead of him, and after reaching it and running back, the starting-point O will be moving toward him. It is quite obvious that each runner will have to travel farther in the second case than in the first. Calculation shows that the runner S, from O to B and return, has really a little more distance to travel than R from O to A and return. Now it was specified that both runners have exactly equal velocities; therefore R should return to the starting-point O; now moved to O^1, a little before S, who has a slightly greater distance to travel. If, however, experiment were to show that both runners returned at exactly the same instant, how would the unexpected result be explained? It will be remembered that the sides of the square are

composed of rods capable of sliding over each other. If, then, some power were to push the side containing B toward O by an amount that would exactly compensate the extra distance that S has to run, it would make no difference to R, and the simultaneous return of the runners would be easily explained.

In the Michelson-Morley experiment (Fig. 14), two rays of light replace the runners. A ray of light from a source L striking a thinly silver-plated glass plate O will be divided into two parts. One of these, R, will be reflected by the silver to the mirror A, by which it will be reflected back again to O, through which it will pass to E. The other part of the light, S, will pass through O to the mirror B, where it will be reflected back to O and again to E. The whole apparatus is mounted on a rigid block of stone which is carried by the earth in the west-east direction through space. The block of stone was floated on mercury so that it could be rotated without producing strains. If the earth were at rest, the two rays R and S ought to traverse their respective paths and return to O,

or to E, where they are observed, in the same time. But since the earth has an orbital velocity in the west-east direction of 18.6 miles per second, the

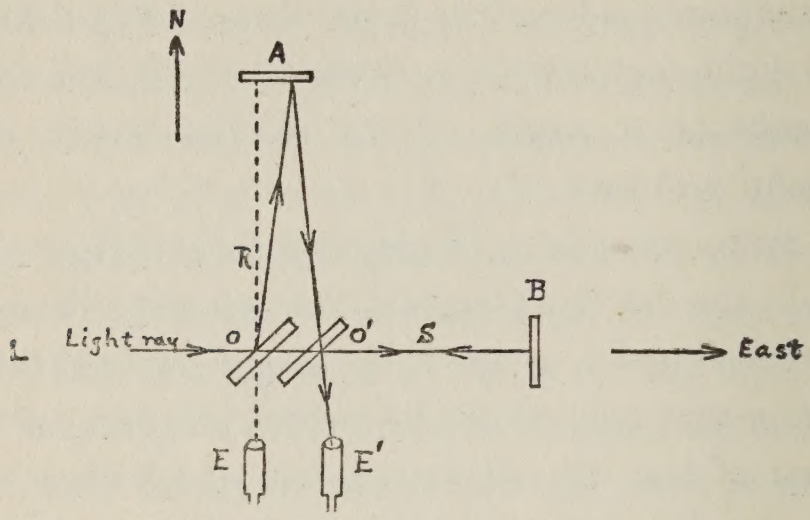

Fig. 14. The Michelson-Morley experiment. The ray of light L divides in two parts, R and S, at the glass plate O. The motion of the earth in the east direction carries O to O^1. The interference bands of the rays R and S after reflection from the mirrors A and B are viewed in the telescope E while it is carried to the position E^1.

ray S ought to return to E a little later than R. Experiment showed, however, that both returned at the same instant.

The question naturally will be asked: How can the equality of the intervals of time of return of

the light rays be measured with exactness when they travel with the velocity of 186,000 miles per second? For in the experiment the lengths of their paths were made only about 30 feet, and the time for light to travel this short distance would be about one thirty-millionth part of a second, a quantity so small that it is far beyond our ability to measure.

In the diagram (Fig. 14) the two rays of light waves, R and S, come together at E. In this condition they may be made to interfere, so that the crest of one wave is exactly over the trough of another (Fig. 15). Each light wave will neutralize the other at regular intervals so that bands of darkness will be produced alternately with bands of light, presenting an appearance like that in Fig. 12. Coloured interference bands are familiar to every one from their occurrence on soap bubbles, on thin films of oil on water, or on a fresh film of petrol on a wet pavement.

If the bands formed by the interference of the two rays of light at E in the Michelson-Morley experiment are closely observed, while the stone

block is being rotated so that the ray R becomes in turn the ray travelling west-east and S the ray

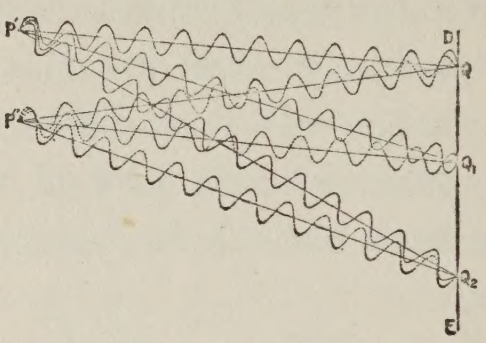

Fig. 15. Interference of waves. P′ and P″ are two sources of waves of light which proceed to Q, Q_1, and Q_2 on the screen DE. At Q the waves arrive with their crests together and at Q_2 with their troughs together. In both cases the waves will reinforce each other and produce patches or fringes of light on the screen. At Q_1 the waves from P′ and P″ arrive with crests opposite troughs and so neutralize, or interfere with, each other. Therefore darkness will result on the screen at points like Q_1. The alternation of fringes of light and darkness produced is shown in Fig. 12.—From Watson's *Textbook of Physics* (Longmans, Green and Company).

travelling north-south, they ought to move perceptibly, if there is any difference between the times taken by the two rays of light in returning to their starting-point or, what is the same thing,

to the place of interference. No such effect was observed to any significant degree. Calculation proved that if a velocity existed between the earth and the ether even as small as a mile per second, instead of the known velocity of 18.6 miles per second, it could have been detected. The experiment showed no measurable difference at all; that is, it gave what is called a negative result, and consequently it was regarded as a failure. But why did it fail? The explanation subsequently offered independently by Fitzgerald in Dublin and by Lorentz in Holland stated that while the molecules of the stone support remained steadily in their usual places in the north-south direction, they were at the same time pressed closer together in the west-east direction on account of the motion of the stone through space, by exactly the same amount as the distance traversed by the ray S was greater than that travelled by R. For this remarkable reason the two rays of light travelled in reality through equal distances, and not through unequal distances as they had been supposed to do. Since experiments must always be performed with

matter of some kind, the Fitzgerald-Lorentz contraction will invariably occur, so that by no possibility can the experiment ever succeed in showing any difference between the times required by the two rays of light to traverse their paths in the directions specified.

About ten years after this suggestion had been given to explain the failure of this skillfully devised attempt to measure the absolute motion of the earth, Einstein put forward his special theory of relativity, in which the Michelson-Morley experiment was viewed, not as a failure, but as a brilliant success. The first principle of relativity, which he deduced from the experiment, now so differently regarded, states that absolute motions, with the single exception of the velocity of light, are impossible to measure or even to detect; that the observed motions in the universe are all of a relative nature. The Michelson-Morley experiment therefore was a decisive demonstration that any attempt to detect absolute motion would invariably be frustrated by the very nature of the interrelationship of matter and space, unless,

indeed, by some magic device Michelson could go out into space and make his measurements by observing the earth travelling past him with its velocity of 18.6 miles per second. Instead of being regarded as the most conspicuous of a series of failures to attain its purpose, the experiment is now established as one of the foundations of the new system of the universe. There is one additional point to mention in regard to this justly famed experiment. The difference between the lengths of the two paths, OA and OB, when the apparatus is in motion, is measured by terms involving the ratio $\frac{V^2}{C^2}$ where V is the velocity of the apparatus, or of the earth to which of course it is attached, and C is the velocity of light. When the terms are squared, as they are in this case, it is known as a "second order" effect. If the quantity had been $\frac{V}{C}$, as in the Bradley experiment, it would be called a "first order" effect. The difference between effects of the first and second order may be shown effectively by inserting in the two

expressions the numerical values. We then have: $\frac{V}{C} = \frac{18.6 \text{ miles per second}}{186{,}000 \text{ miles per second}} = \frac{1}{10{,}000}$, first order, and $\frac{V^2}{C^2} = \frac{(18.6)^2}{(186{,}000)^2} = \frac{1}{100{,}000{,}000}$, second order. The first ratio of one to ten thousand is quite small, but it may be easily measured. The ratio of one to one hundred million is immensely smaller and far more difficult to measure. But when it is measured it reveals much more minutely the relation of the phenomena of nature to one another.

The Michelson-Morley experiment was the first attempt to measure directly a second order effect of this kind, and for this reason it occupies its pre-eminently conspicuous and fundamental position as the corner stone of the special theory of relativity. Other experiments, also capable of measuring second order effects, have since been devised, which, in all cases but one, confirm the negative, or perhaps we should now say the positive, results first obtained by Michelson and Morley.

The Michelson-Morley experiment has lately been repeated by Dr. D. C. Miller at several altitudes, including the summit of Mount Wilson in California. Contrary to the results previously obtained, he asserts that measurable velocities of the earth relative to the ether were found which increase in magnitude with the elevation at which the observations were made. The velocities obtained, while too large to be ignored, are yet too small to convince those who have intensively studied relativity that the theory, which has now achieved such notable triumphs, is in any essential respect unsound. But no theory of science can long endure if a single pertinent fact proves to be irreconcilable with it. Further work should therefore be undertaken to remove any uncertainty from this fundamentally important experiment. Probably the most that can be expected in any case is to require in the special theory of relativity some modification or extension.

From the Michelson-Morley experiment it is evident that, regardless of the motion of the earth, light itself travels with the same velocity in all

directions in space. Thus the velocity of light becomes a universal constant, perhaps the most fundamental of all the constants of nature, unless indeed a greater velocity may in the future be found which could be made use of in the measurement of that of light. This characteristic of light, the constancy of its velocity, has been elevated by Einstein into his second postulate, or principle of relativity.

Up to this point we have been considering the ideas and discoveries which have led to the development of relativity. To utilize in any adequate manner the two basic principles which have been mentioned would require extensive mathematical treatment, which obviously cannot be introduced here. All that can be done is to state some of the consequences of the theory of relativity which are susceptible of popular exposition.

THE FUNDAMENTAL UNITS OF MEASUREMENT

In the study of physics the numerous and often complex units of measurement can be resolved into three fundamental terms of simplest character,

length, mass, and time. The standards of these units, the foot, pound, and second in the English system, and the centimetre, gram, and second in the French or metric system, have ever been regarded as absolutely constant in magnitude under all conceivable conditions. With relativity, constancy of magnitude no longer obtains. Lorentz has derived three equations, called the Lorentz transformations,[1] which express the exact amount by which the mass of a body, or the length of a rod, is altered when in translatory motion, or an interval of time as it is measured by a moving clock or other time-indicator.

[1] The Lorentz transformation for length is:

$$l = l_0 \sqrt{1 - \frac{V^2}{c^2}}.$$

This formula expresses exactly what will be the length, l, of a rod, which at rest has a length of l_0, when it is moving in the direction of its own length with a velocity of V miles per second. The velocity of light, 186,300 miles per second, is represented by c.

The Lorentz transformation for mass is:

$$m = m_0 \left(\frac{1}{\sqrt{1 - \frac{V^2}{c^2}}} \right)$$

in which m_0 is the " rest-mass " and m is the inertial mass. The third transformation for time is given on page 82.

Suppose a rod, whose rest-length is one yard, to be moving in the direction of its length with a velocity of one mile per minute. Since its motion will cause contraction, what will now be its length? By placing these values in the formula, we shall find its length to be diminished by about 0.000 000 000 000 4 yard; that is, its new length is only 0. 999 999 999 999 6 yard. At a velocity of one mile per second the length would be reduced to 0.999 999 999 98 yard. If the velocity were increased to 161,000 miles per second, the length of the rod would thereby become just half a yard. Should the velocity of the rod become equal to that of light it would shorten to nothing. As all the matter of the rod would then be squeezed tight together, the molecules would be crowded into an infinitesimally small space, a condition which would make its density infinitely great. Since the earth is moving through space in the west-east direction with a velocity of 18.6 miles per second, its equatorial diameter of 7,927 miles is less by about 2.5 inches than it would be if the earth were at rest. If we lie down in the same direction our

bodies also will become somewhat shorter than they are when placed in the north-south direction. In general, all material bodies in translatory motion become shorter or more compressed as the velocity increases; and when travelling with the speed of light they will flatten into planes. Among bodies in relative motion, that one is at rest relatively on which the same rod appears longer than on any other. A spherical body also which is at rest appears spherical to an observer who is likewise at rest. But to a person who is in motion, it would appear to be flattened in one direction. The theory of relativity thus recognizes no absolute but only a relative shape.

The Lorentz equation for mass is a little different from that for length, and expresses generally the fact that the inertial mass of a body becomes greater as the velocity increases, whereas the length of a body under the same conditions becomes less. As a body does not obtain additional matter by increasing its velocity, the question of what is meant by the relativity increase of mass naturally arises.

When a body is at rest, force is required to set it in motion, that is, to overcome its inertial resistance. Inertia is that property of matter which causes a body when at rest to resist being set in motion, or when it is in motion to resist being stopped, or having its velocity either increased or diminished, or having its path changed from a straight line into some form of curve. Inertia is shown by a person being apparently thrown backward—really remaining at rest in space—when the car in which he is standing suddenly starts, or apparently being thrown forward in a straight line—really continuing his motion—when it suddenly stops or turns a sharp curve.

The rate at which a body acquires velocity under the action of force is called acceleration, a term which has become universally familiar because of its application to the starting of motor cars. The force required to move a body is measured by multiplying together its inertial mass and its acceleration. A certain force must be applied to a mass of one pound in order to accelerate it from rest to a velocity of ten feet per second at

the end of one second. To give the same body in one second an additional velocity of ten feet per second would require, according to the Newtonian laws, the application of the same force whether the body already had a velocity of ten, a hundred, a thousand, or a million feet per second.

According to the theory of relativity, however, this is not correct; for the body which has a rest-mass of one pound acquires with increasing velocity an increasing inertial mass so that a continually larger force would be required to give it the same acceleration, or increase of velocity, as before. At the considerable velocity of one mile per minute the pound would have an inertial mass of 1.000-000 000 0004 pound, an increment far too small to be detected. Even at the velocity of a mile per second the inertial mass would become only 1.000-000 000 02 pound. When, however, the velocity of the body approaches that of light the inertial mass assumes large proportions. Should the velocity reach 161,000 miles per second the inertial mass of the original pound would become two

pounds, while at the velocity of light it would be infinitely great.

Obviously the increase of inertial mass due to ordinary velocities is far too small ever to be taken into account. But in the study of electrons of which atoms are partly built, velocities above 161,000 miles per second are actually encountered which of necessity must not be neglected, as these calculations show.

VELOCITY OF ELECTRON

At						Rest-Mass	= 1
161,000 miles per second, inertial mass of an electron							= 2
175,650	,,	,,	,,	,,	,,	,,	= 3
180,400	,,	,,	,,	,,	,,	,,	= 4
182,500	,,	,,	,,	,,	,,	,,	= 5
184,400	,,	,,	,,	,,	,,	,,	= 7
184,800	,,	,,	,,	,,	,,	,,	= 8
185,200	,,	,,	,,	,,	,,	,,	= 9
185,500	,,	,,	,,	,,	,,	,,	= 11
185,900	,,	,,	,,	,,	,,	,,	= 15
186,300	,,	,,	,,	,,	,,	,,	= infinity
				(*velocity of light*)			

It is also true that if an electron at rest is a sphere, it will gradually become flattened more and more into a disc as its velocity increases, and

at the velocity of light it will become infinitely thin and dense.

What is true of a single electron is equally true of a rest-mass of any magnitude. At the velocity of 185,900 miles per second the inertial mass of one pound would be 15 times as great as when it is at rest. In acquiring an additional velocity of 400 miles per second the inertial mass rapidly increases until it becomes infinitely great. The forces of the universe all combined could not give to a grain of sand, travelling with the velocity of light, the least acceleration or increase of velocity or even deflect it by a hair's-breadth from its rectilinear course. In a world moving with such a velocity, all bodies would travel in straight lines. Curvilinear motions of any kind would be impossible.

Imagine two bodies, each travelling with the velocity of light, to meet in a head-on collision. Here we have an illustration of the ancient question of what will happen when an irresistible force meets an immovable body. It is not likely that this interesting query will ever receive an experimental

answer. As something would happen, however, it may be suggested that the two bodies would cease to exist as matter and would travel away at right angles to the direction of impact in the form of radiant energy. Possibly this may sometimes be the fate of colliding electrons in the atom, unless, as it is now suggested, the electrons themselves have no material existence but consist of minute permanent wave patterns in space.

Novel as are the relativity views of the inconstancy of length and mass, it is still more surprising to learn that time experiences changes of precisely the same character. For, according to the theory of relativity, seconds of time measured by a clock which is at rest have a shorter duration than those measured by the clock when it is in translatory motion.

Intervals of time, such as the second, are always measured by some event, or by the duration elapsing between two events, that is, two occurrences in nature, such as the extreme positions of a swinging pendulum, or the oscillation of the balance wheel of a watch, or the revolution of an electron around

the central nucleus of an atom, or the rotation of a planet, such as the earth, on its axis. Any of these, or similar devices, may be styled a clock. To avoid confusion in the present discussion, the term "proper second" will be employed for the ordinary interval of time, called by that name, which is measured by a clock at rest on the earth. The term "translatory second" will be used for the similar interval of time as it is measured by a clock which is not at rest but is carried, for example, on a moving train. The measurements of time by a clock at rest are known as "proper time."

Let two clocks which are at rest be adjusted to measure proper seconds exactly. To one of them is then given a velocity such as one mile per minute. The translatory seconds of the moving clock will have a greater duration than the proper seconds of the clock at rest. The difference in duration between the proper and translatory seconds can be calculated from the Lorentz equation for time. Since this equation has the same form as the Lorentz transformation for mass, the numbers obtained for the variation of mass with velocity

will also represent the increased duration of the translatory seconds of clocks moving with the same velocity. Thus if the clock has a velocity of one mile per minute, the duration of its translatory second will be increased to 1.000 000 000 000 4 proper second. At the velocity of 161,000 miles per second, the translatory seconds will be two proper seconds in duration. When the velocity of the clock becomes 185,900 miles per second, each translatory second will be equivalent to fifteen proper seconds of the clock at rest. At the velocity of light, which is the limiting or the greatest possible velocity of the clock, a single translatory second will last forever. In a world travelling with the velocity of light, all time measurements alike would be infinitely long, a second would become eternity, and relative terms such as minute, hour,

[1] The Lorentz transformation for time is:

$$t = t_0 \left(\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \right)$$

where t_0 represents the proper time as measured by a clock at rest and t is the translatory time of the clock when it is moving with the velocity v.

and day would be meaningless. In such a world duration would no longer possess significance. Time indeed would be no more.

It is evident that what an observer would call the simultaneous occurrence of events on two planets which are travelling with different velocities could not possibly be so related, not only on account of the fact that light requires time to travel, but also because the two clocks which timed the events on the different planets could not be indicating time intervals of the same duration. How can an earth observer possibly judge events to be occurring simultaneously on the earth and a star, when the light just entering his eyes left the star a hundred, a thousand, a million, or even, it is now estimated, a hundred and fifty million years ago, and when the clocks on the two worlds, by which the duration of events was measured, would not be keeping the same time? The correct judgment of simultaneity of events would be possible only by an observer located equally distant from the two worlds which were moving with equal velocities toward or away from him, or by an

observer, for example, situated at the equator of the earth, watching events, and the clocks which timed them, which were occurring at points equally distant north and south of that line. For at the equator a clock, which has a translational velocity of one thousand miles per hour due to the rotation of the earth, will indicate longer seconds than another clock at the poles, where it has no translational velocity arising from the earth's rotation. The translatory seconds of a clock will therefore constantly increase in duration as it moves from the poles to the equator. Hence it follows that translatory seconds will have the same duration only when the two clocks are equally distant from the equator.

It may be urged that the differences in the duration of translatory seconds under all ordinary conditions are far too small to be considered. From the practical standpoint this is correct. Science, however, can make no progress if its theories are based on appearances or careless approximations and not on the utmost attainable accuracy of knowledge.

Suppose now that we consider a case where two observers describe the same events from different standpoints. It so happened one day when riding in a street-car along a straight track that I noticed through the wide opposite window a man's hat bobbing vertically up and down with rhythmical motion. The bobbing hat suddenly appeared at the forward edge of the window, moved slowly backward, then for a few seconds remained stationary except for the regular bobbing motion, again moved slowly forward, then more rapidly and finally disappeared. As I saw this, I am sure that my description of its motion is correct. If the man under the hat had been asked for his description of the event, he would indignantly have denied that he was walking backward, then stopping, and finally moving forward. He would have said that the street-car, which was moving faster than he was, at first caught up to him, travelled for a few seconds at the same speed, then went more slowly, and finally stopped, while all the time he had been walking steadily forward.

Obviously our descriptions of the event do not

agree. Here are the materials for a dispute, probably ending, as such arguments usually do, by each contestant's expressing the opinion, or, at least, holding the conviction, that his opponent was strangely lacking in the power of reasoning. If a third person informs us that the dispute can readily be settled by referring both descriptions to the relatively stationary earth, we shall no longer disagree. Each observer is correct in his private description of the event, and both are reconciled with reference to the earth.

Every event or process of nature cannot be referred to the earth, and if we are to have a consistent system of the world agreeable to all observers, it is imperative to discover a quantity fixed, unalterable, and of so universal a nature that all events can be referred to it as a common basis of reference. Since the absolute motion of any material body is incapable of detection, and measurements of mass, length, and time vary with velocity, there remains for reference only the velocity of light in space or in a vacuum, since it is invariably a fixed quantity and its measurement

is independent of the velocity of the source of light or of the observer. The constancy of the velocity of light, therefore, as remarked before, becomes the second fundamental principle of relativity.

It certainly seems absurd to say that no velocity greater than that of light can possibly be attained by matter. If the earth were moving with the velocity of light, a person residing upon it might be supposed by walking in the same direction to add his own velocity to that of the earth. However, if we calculate the resultant motion of the person under these conditions we find that his additional velocity adds nothing to that of light. It always reduces to that fixed quantity. No velocity involving the transfer of matter or energy can by any possibility be greater than that of light. With assumed velocities greater than this value, it can be proved that we should see effects before their causes operated; we could witness events before they happened! My colleague, Professor A. H. R. Buller, F.R.S., has picturesquely set forth this result in poetic form:

"There was a young lady named Bright
Whose speed was far faster than light;
She set out one day
In a relative way
And returned home the previous night."

These conclusions being manifestly absurd, we are led to regard the velocity of light as the ultimate or limiting but unattainable velocity of the material world. Greater velocities than this are conceivable, however, but only under the condition that they do not involve the transfer of either matter or energy. The measurements in physics, such as those of time, length, mass, velocity, involve the transmission of signals. In determining velocity, for example, the time of beginning the motion as well as that of finishing it must be signalled in some way to the observer. The importance of light in relativity is primarily due to the fact that it has the greatest measurable velocity with which we are acquainted; and as its velocity in space is constant under all conditions it is universally adapted for the purpose of signalling. Hence the speed of light appears in the Lorentz

transformation equations for mass, length, and time as the limiting velocity of the material world. Should a greater velocity exist and be measurable, such as that of the transmission of gravitational force, it might in turn be used as the agency for signalling and thus assume the place of light. The velocity of propagation of gravitation is so great that it escapes detection and may indeed be infinite. An infinite velocity is beyond our power to employ for such a purpose. Should it prove to be finite but surpassing even the great velocity of light, it is conceivable that its use would lead to the discovery of third-order effects of excessive smallness by which the constitution of nature in a still profounder degree might be disclosed.

MATTER AND ENERGY

The world of nature, apart from life, has usually been believed to consist of two entirely different but invariably associated entities which are called matter and energy. Matter is found to exist in ninety-two simple or elementary forms, of which the hundreds of thousands of compound

substances in the world are composed. The atomic structures of the elements, which resemble miniature solar systems, increase in complexity in a perfectly regular manner. The number of planetary electrons in each atom is denoted by one of the whole numbers from 1 to 92. Hydrogen, the lightest substance, with one planetary electron, has the atomic number 1, whereas uranium, the heaviest substance at present known, from which by a process of spontaneous atomic disintegration radium is formed, occupies, with its 92 planetary electrons, the last position in the series.

The energy of the world, by which all changes are effected, all work accomplished, also exists in many forms, such as heat, light, sound, electrical energy, and the kinetic energy of moving bodies, which can readily be transformed from one type to another.

Two laws governing these entities have been discovered, which express the fact that matter and energy, while subject to unlimited transformations, can be neither created nor destroyed by any finite power. Their quantities in the universe, if it is

finite in extent, were believed to be absolutely and eternally fixed. These laws are known as the conservation of matter and the conservation of energy. The former, which originated in France, is the most basic principle of science formulated in the eighteenth century; while the latter, suggested in Germany but established in England, is likewise the most fundamental and far-reaching discovery of the nineteenth century in physical science.

Since our knowledge of the world is gained exclusively through the senses, such as vision, touch, hearing, taste, and smell, it follows from the nature of the constitution and mode of action of our nerves and brain, by which our senses are excited, that without matter we should never have known energy and without energy we should never have known matter.

The principle of relativity enforces the surprising conclusion that the interactions of matter and energy are so intimate in their nature that they cannot be separated. Each is inextricably bound up with the other. From the new point of view every increase in the energy of a body that

originates wholly from changes within itself involves an equivalent decrease in the quantity of its matter or, as it is usually termed, its mass, and a decrease in energy is accompanied by an increase in mass. All energy possesses mass; all mass possesses energy. The hitherto separate quantities, mass and energy, have become consolidated into a single entity of which they are two manifestations. The conservation laws likewise have been unified into a single principle. From this new law of the "conservation of mass-energy" we learn that neither the quantity of matter nor the quantity of energy of the universe is constant, but only their sum. Mass may be transformed into energy and energy into mass, but always in strictly equivalent proportions. The verification of this important principle by experiment has not yet been accomplished. The diminution in mass through any observable change in the energy of a body is far too small a quantity to be measured by any method yet devised.

The expression for the energy of motion of a moving mass, that is, its capability of doing work,

is usually formulated thus:

$$\text{Kinetic Energy} = \tfrac{1}{2} M_0 V^2$$

In this formula M_0 represents the mass of the body and V the velocity. If the velocity is doubled the energy would become four times as great, and it would be able to do four times as much work of any kind.

According to the theory of relativity the energy of motion of the enormous numbers of electrons in the atoms is an immensely larger quantity than that due to the motion of the mass as a whole, for each electron may be moving with a velocity of 150,000 miles, or even more, per second. In this case the energy is expressed by the formula M_0C^2, where M_0 is the mass of the body at rest, or the rest-mass, and C is the velocity of light. This quantity of energy is called the "proper energy," since it is inherent in the body. The proper energy never changes; it is the same whether the body is cold or hot, at rest or in motion. As an illustration of the vast difference between the two quantities of energy, it can readily be calculated that the proper energy of a rifle bullet whose velocity

is 3,000 feet per second is about two hundred billion times as great as the kinetic energy which it possesses.

If we take as the unit of energy a foot-pound, which is the amount required to lift a weight of one pound one foot high, the kinetic energy of a pound moving with the velocity of a rifle bullet, about 3,000 feet per second, is nearly 140,000 foot-pounds, an amount which is capable of lifting a weight of twenty-six pounds one mile high. In contrast with this quantity, the proper energy contained in the same pound of matter is 30,240,000,000,000,000 foot-pounds, which is sufficient to lift over 60,000 *Aquitanias* of 50,000 tons each to the same height.

The proper energy of a body, as noted before, is measured by the expression M_0C^2, which is the first of an infinite number or series of terms expressing the complete energy of the body. The second term, $\frac{1}{2} M_0V^2$, of the series is the ordinary kinetic energy of the body due to its motion as a whole. The third and fourth terms, which are given in the footnote, and the following terms,

which are not calculated, are so small in value at moderate velocities that they are always disregarded. They become large enough to be taken into account only when the velocity of the body begins to approach that of light.[1]

Several thousand tons of coal must be burned in order to obtain sufficient energy to drive a great steamer across the Atlantic. Should some method be devised whereby the proper energy could be released, which at present cannot be done and, indeed, seems quite beyond the range of possibility, the amount contained in a grain of coal would easily suffice to propel across the ocean the greatest liner ever built. A single ounce of coal, by using its proper energy, would have been sufficient to heat a residence from the time of Adam to the present. If this possibility became realized we could then receive our supply of fuel by mail. Let

[1] By expanding the Lorentz transformation for mass (see footnote, p. 73), it is found that the total energy of a moving mass is given by the equation:

$$MC^2 = M_0C^2 + \tfrac{1}{2}M_0V^2 + \tfrac{3}{8}M_0\frac{V^4}{C^2} + \tfrac{5}{16}M_0\frac{V^6}{C^4} + \ . \ . \ .$$

where M_0 is the rest-mass of the body, M is its mass when in motion with the velocity V, and C is the velocity of light.

us fervently hope that should the inexhaustible supplies of proper energy residing equally in all kinds of matter, as well as in coal, become available, the means of control may also be discovered. For if all the energy hidden in one pound of matter were to be released at once, the experimenter, his laboratory, and even his city would forthwith be swept to destruction.

These ideas have been applied to the problem of the solar radiation. The sun is a vast mass from which streams of light and heat energy are being radiated. It has been calculated that the radiation reduces its mass by about four million tons every second. At this rate the mass of the sun, if its present temperature be maintained, will radiate itself away in ten thousand billion years. Making allowances for every interfering possibility, a more reasonable limit to its future existence would be one hundred billion years—a time sufficiently long to allay anxiety.

But the introduction of a new theory always gives rise to new and unexpected problems. If the sun is radiating away its own mass, so also are the

stars, and the process has been going on for vast ages. By this time the radiated mass must have reached colossal proportions and ought to be found as mass or energy somewhere in the universe. Yet no trace of any gravitational influence exerted by it can at present be detected, no evidence of its existence discovered.

Though the quantity of matter comprising the visible universe is exceedingly great, the extent of space is vastly greater. Even if the matter or its equivalent radiation, therefore, became uniformly distributed, it might be difficult or even impossible to detect it by any experimental methods now at our disposal.

SPACE

It has been pointed out that the idea of a universal ether was developed as a logical necessity to afford a carrying medium for light and force actions. As a further necessity the ether was assumed to be uniformly distributed throughout all space. Newton fortified his system of the world with a definition of space: "Absolute space, in its

own nature, without regard to anything external, remains always similar and immovable."

Space therefore was regarded as one concept, and the ether as an entity which filled the space. Conceivably the ether might be withdrawn and still leave space, only in a condition of absolute emptiness, much the same as air or water might be withdrawn and leave the volume of the container. The special theory of relativity, which is restricted to uniform motions in straight lines, does not require any reference to an ether. Its conclusions are independent of any assumption of a medium whatever. So also in the complete or general relativity philosophy no mention of an ether need be made; the only concept required is that of space. It is asserted in that case that space itself must be endowed with those properties which make it merely the equivalent of the ether, so that all that is accomplished is a change of name. This, however, is not quite the same idea. The ether might be removed from space, while space would still remain. If space were removed the universe itself would vanish.

TIME

The fundamental philosophical concept of time has also had its character changed. Can we possibly regard time as a pure concept without reference to events or natural processes of some kind? It is much to be doubted. If one tries to think of time in itself, the mind seems inevitably to swing to some natural event connected with time. So essential is time in any system of the world that Newton defined it also with care: "Absolute, true and mathematical time, of itself, and from its own nature, flows equably without regard to anything external, and by another name is called duration."

This definition, often criticized, is now regarded as singularly misleading. It implies time to be the same everywhere under all conceivable conditions, whereas it seems impossible to avoid the conclusion that all moving systems enjoy their own local times, which differ, as we have seen, according to velocities. It has become necessary, therefore, to establish the concept of time upon a basis radically different from that formerly prevailing.

THE SPACE-TIME WORLD

Are space and time really separate and independent entities as they have hitherto been regarded? "Not so," say the relativists; "they are connected in a very peculiar but remarkably significant manner which has been realized only for a very short time." This we may now consider.

The mind enters into conscious relationship with the external world through certain of the senses, the chief of which in this connection are vision and touch. By the exercise of these senses, accompanied necessarily by some innate power of the mind, we obtain our conception of space and of the world of three dimensions, usually described as length, breadth, and height. From infancy we are acquainted with the sensory world of this type, and on this account, as well as by the constitution of the mind, we are able easily to picture in the imagination points of no dimensions; curved and straight lines of one dimension; areas such as triangles, circles, parallelograms, etc., of two dimensions; volumes such as cubes,

spheres, cylinders, pyramids, etc., of three dimensions. Of all these we may make models which fully satisfy our senses. But when we try to picture to our minds a fourth dimension of this type the capacity of the imagination is exceeded and complete failure is experienced. The mind, however, possesses the additional power of recognizing the simultaneous and successive occurrence of events, and to the concept of duration involved is given the name of time.

It is obvious, therefore, that the ancient system of geometry, developed chiefly by Euclid, once the exclusive pursuit of philosophers but now a commonplace subject of study in the schools, which consists of the investigation of the properties and relationships of points, lines, areas, and volumes involving no more than three dimensions, is based fundamentally upon the capability and, at the same time, the limitation of our senses and imagination. Euclidean geometry and sensory psychology in reality are counterparts of each other; the former is circumscribed and conditioned by the latter. Euclidean geometry thus describes

and relates the properties of space which are evident to the senses ; it is therefore a restricted or special geometry adapted to the world of experience.

If reason may rely with confidence upon its concepts when supported by the evidence of the senses, may it not also be justified in relying upon its concepts even when they transcend the power of the imagination ? If reason and experience together can rely upon the truth of the geometry of three dimensions, may not reason alone be trusted with the concept of an additional fourth dimension, even though it cannot be pictured by the imagination or apprehended by the senses, but nevertheless can be made the subject of exact mathematical reasoning ?

Such a geometry, non-Euclidean as it is called, has been developed chiefly by Riemann within the last century. This, while including three dimensions, more naturally concerns itself with four. The additional fourth dimension, of the same type as the familiar three, has not conducted the mind to anything outside of itself ; it has only pictured

a world which seems to have no counterpart in reality and certainly none in experience. But by an ingenious though very simple device a method has been developed by which time has been given a geometrical interpretation which enables it to be incorporated with the traditional three dimensions as a fourth dimension whose nature is familiar to us. There has emerged in consequence a world of four dimensions, three of which are descriptive of space and the fourth consisting of time, dressed as it were in a new and unfamiliar garb. Hitherto kept separate from each other, they have now been combined by Minkowski, one of Einstein's early teachers of mathematics in the University of Zurich, into a new world-concept which has been incorporated by Einstein into his theory of relativity. Every event that happens in the world has both a spatial and a temporal aspect, which are the four components of a single occurrence. "From this day forth," said Minkowski, in announcing his new world-theory, "space taken by itself, and time by itself, are to become mere shadows, and only a kind of union of both is to retain inde-

pendence." As events are continuous from point to point in space and from moment to moment in time, the new relativity world is referred to as a "four-dimensional space-time continuum," three of its dimensions comprising space, and one time.

I may make an appointment to meet a person in a certain office on the tenth floor of a building on the corner of two intersecting streets. Two of the spatial coordinates of the office are the streets extending north-south and east-west, and the height of the tenth floor above the ground is the third. To be at that point in space does not mean that I shall meet the person unless the time of appointment also is clearly specified. Time therefore is equally important with space; why should it not also be regarded as a fourth dimension? Upon first thought there is one aspect in which space seemingly differs from time. Apparently I can repeat the spatial part of the appointment but never the temporal. In no conceivable way can I recall nine o'clock yesterday morning. It becomes clear, however, that I can only relatively repeat the spatial part of the event, for since the appoint-

ment was kept the earth has steadily rotated, carrying with it the building and the city, while the planet itself has moved to a far different point in its orbit in space. The original point will never be occupied by us again. In a world at absolute rest an event can be repeated in space but not in time; at the velocity of light an event can be repeated in time but not in space; at all the infinite series of states between these two extremes an event cannot be repeated either in space or in time. It can only be imitated.

THE CURVATURE OF THE SPACE-TIME UNIVERSE

Another aspect of the universe from the standpoint of relativity must now receive attention. The shortest distance between any two points on a plane of two dimensions is the straight line joining them. If we bend the plane into a segment of a sphere we can still treat the surface from the standpoint of a two-dimensional world, as is habitually done in surveying the surface of the earth. If we keep to the curved surface the shortest distance

now is not a straight line but an arc of a "great circle," that is, a circle whose plane passes through the two points and also through the centre of the sphere. Navigators, of course, are aware of this fact and always endeavour to lay their ships' course on the arc of a great circle. The development of aviation on a world scale will soon familiarize all people with these ideas. The shortest air-line from Winnipeg to Japan, for example, runs over the south part of Alaska. From London to Australia the shortest route passes over Petrograd. The shortest line on a curved surface, therefore, can be accurately defined; it is called a geodetic line or a geodesic. We are familiar with two-dimensional curved surfaces embedded in our three-dimensional world, for it is a two-dimensional surface that covers the three-dimensional earth. What will hinder us from forming the concept of a three-dimensional space embedded in a world of four dimensions, such as the Minkowski world in which space and time are inseparably linked together? To picture this conception by our imagination is indeed beyond our present power.

This, however, does not prevent it from receiving accurate mathematical treatment.

If the universe had comprised only space without matter it would have been indefinitely large or indeed infinite in extent, and exactly alike in every part. The effect of the presence of matter has been ingeniously assumed by Einstein to impress a curvature on the space-time world whose amount depends upon the quantity and distribution of the matter, or upon the strength of what we ordinarily call the gravitational field of force. The curvature, too, is greatest close to the largest bodies such as the sun and the stars. Since the four-dimensional world has curvature, geodetic lines in it must be possible; and these lines are the "world-lines" of moving particles, or the paths in which they move.

The elliptical orbit in which a planet moves, which was Kepler's great discovery,is not in reality the "world-line" of the planet. For a world-line has meaning only with reference to the four-dimensional world and is unimaginable, whereas the elliptical orbit is described by the planet in the

three-dimensional world of common experience.

Every person knows that the appearance of a building depends on the position from which he looks at it. To an observer in one position an ellipse may appear as a circle, or a circle as an ellipse,

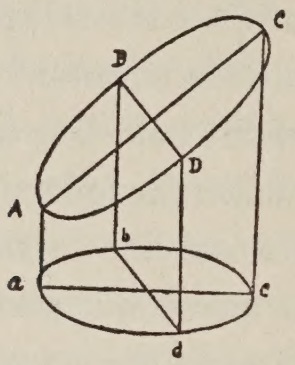

Fig. 16. Projection of the ellipse ABCD into the circle abcd. The circle may also be regarded as projected into the ellipse.

while if he were situated in the plane of the curve each would appear as a straight line. These facts are usually expressed in the statement that the projection of an ellipse upon a plane may be a circle, or the projection of a circle may be an ellipse, or if the curves were placed vertically on edge the projection of each of them would be a straight line (Fig. 16). The elliptical projection

of the circular disc of the sun may often be seen on the floors or walls of a room in the luminous patches formed by rays of sunlight passing through small holes in the window-blind. If one could travel into space, the earth's orbit, which in three-dimensional space is an ellipse, would appear as a straight line, a circle, or an ellipse, according to the position of the point of view. If our imagination could visualize the four-dimensional space-time world, the world-line of the earth, as seen from our present viewpoint, would appear not as an ellipse but as a more complex orbit. The elliptic orbit of a planet may therefore be regarded as the projection of its space-time orbit or world-line from the four-dimensional into the three-dimensional world.

These ideas of a four-dimensional world may seem remote from our experience and even fantastic, since they are beyond the present power of our imagination. Perhaps they would have remained refined abstractions suitable only for the exercise of highly mathematical minds, but for the astonishing fact that from them Einstein has

deduced a law of gravitation somewhat different from the simple classical law of Newton. It may be remarked that Newton never derived his law from mathematical reasoning. He, and indeed others as well, assumed it to be true, and then by trial he proved it to be accurately applicable to all types of astronomical calculations. With the new law it is altogether different. From fundamental principles Einstein for the first time has derived a law of gravitation which in part is the same and in part essentially different from that of Newton.

WEIGHT AND INERTIA

Einstein's law rests partly on the interpretation of a principle always assumed to be true but never regarded as possessing any particular significance until Einstein employed it with such brilliant success. This principle has received the minutest verification by an experiment of extraordinary accuracy due to Baron Eötvös, the Hungarian physicist and greatest man of science, which in delicacy and importance is quite comparable with

that of Michelson and Morley. As the latter experiment is the foundation of the special theory of relativity, so the former is the experimental foundation of the general theory. To bring out the significance of this notable experiment a brief discussion of two of the most fundamental ideas in physics is necessary.

The mass or quantity of matter in a body has always been regarded from two points of view. The first and most familiar of these is the gravitational attraction exerted by the earth, or, more accurately, between the earth and the body, which gives the mass its weight. The second is the inertness of the mass, by which is meant its tendency, if at rest, to remain at rest or, if in motion, to move with uniform speed in a perfectly straight line. The former is called its gravitational mass and the latter its inertial mass.

Measuring masses by their weights is the most common of mercantile operations, perfectly familiar to us in buying a pound of sugar or any other commodity. It is not so generally recognized that the magnitude of the gravitational mass is

an accidental value entirely due to the size and density of the earth. If, for example, a man weighing one hundred and fifty pounds on the earth were to be transferred to the moon, where gravity has just one-sixth of its earth-value, he would weigh only twenty-five pounds. If he were to visit the planet Jupiter, where gravity is two and one half times the earth-value, his weight would become three hundred and seventy-five pounds. If, finally, he could travel to the sun, where gravity is twenty-seven and a half times the earth-value, he would collapse under his own weight of a little over two tons.

The idea of inertia is also very familiar in such common occurrences as the flying of mud from a rotating wheel, or the removing of snow from one's shoes by stamping on the ground, thus suddenly stopping the foot while the loosely adhering snow continues its motion. It is also familiar, as remarked before, from the motions of our bodies in a street-car when it suddenly starts, stops, or turns a corner. It becomes a dangerous reality to a passenger when in a motor car collision he

continues his inertial journey through the wind-screen.

In scientific thought these two quantities,

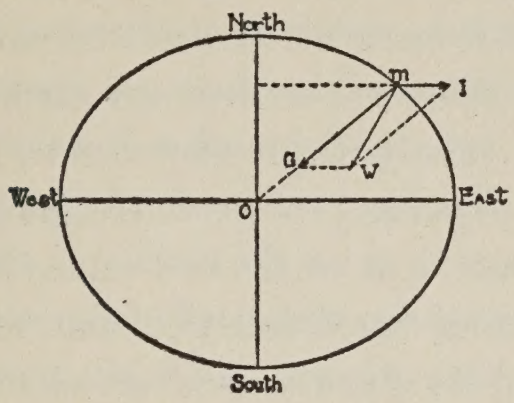

Fig. 17. Diagram of the earth to indicate the influence of inertia on the weight of a body. The earth rotates from west to east on its polar NS axis; m represents a particle on its surface, mGO is the direction of gravitation, mI the direction of the centrifugal force, and mW the direction of the resultant force, or the weight of the particle. The line mI, as drawn, is much exaggerated in length as compared with mG.

gravitational and inertial mass, have always been assumed to be proportional to each other. But the experiment of Eötvös, as interpreted by Einstein, went much further and proved the two to be identical.

The accompanying figure (Fig. 17) represents

a section of the earth which is not spherical but spheroidal in form because the rotation, from west to east, causes an expansion at the equator with a consequent contraction or flattening at the poles. The polar diameter, north-south, 7,900 miles in length, is twenty-seven miles shorter than the equatorial diameter, west-east, of 7,927 miles. A body or particle m on the surface is attracted by gravity toward the centre O of the earth in the direction of the arrow G. This would be the only force acting on the particle if the earth were at rest. But since it is rotating on its north-south axis, the inertia of the particle manifests itself as, or develops, a centrifugal force, acting perpendicularly to the axis in the direction of the arrow I, which partly counteracts gravity both in magnitude and direction. What we call the weight of the particle is really the resultant of these two forces combined, and it is directed along the line W, which does not pass through the earth's centre but lies between the two forces much nearer to G than I, since the gravitational effect is far greater than the centrifugal. Should the earth in

some way be speeded up to seventeen times its present rotational velocity, a condition which would shorten our day to one and a half hours, the centrifugal tendency at the equator, which originates from the inertia of the body, would exactly balance the force of gravity, with the result that the particle would apparently have no weight at all.

Now we cannot change the attraction of the earth or the speed of its rotation in order to study separately by experiment their effects upon the particle. But in the Eötvös experiment it is possible to compare the weight and inertia of particles of various sizes and of different chemical composition. If in all cases it is found by experiment that the direction of the resultant force W never varied in the most minute degree, it would mean that the gravitational and inertial masses of every body or particle are invariably and exactly proportional to each other.

The equivalent of this comparison was made in 1890 by Eötvös in an experiment of extraordinary delicacy and precision. The torsion balance with

which he accomplished this result is a very simple contrivance, as is evident from the accompanying diagram (Fig. 18). A very light beam consisting of a tube of aluminium, BC, about seventeen inches long, is suspended in a horizontal position by a

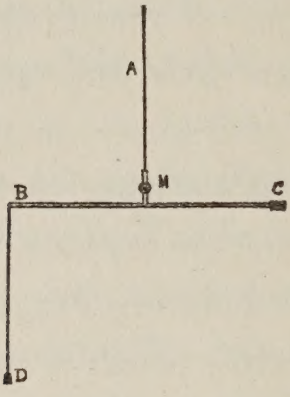

Fig. 18. The Eötvös experiment. Diagram of torsion balance for proving the identity of inertial and gravitational mass.

fine platinum-iridium wire A about 0.0018 inch in diameter, to which a mirror M is attached. Two masses, each about one ounce in weight, one of platinum, C, a metal which is twice as dense as lead, and the other, D, of any desired material, are attached to the beam, the platinum directly to one end, and the second suspended from the other end by a fine wire about twenty-five inches

long. Since the mass D is a little nearer the earth than C, the force of gravity, which is stronger when the mass is nearer the earth, acting on it, will be slightly greater than that acting on C. The effect of the rotation of the earth on these masses will also be unequal so that the platinum, since it is the more distant from the earth, will have the greater velocity of the two, just as a particle on the rim of a rotating wheel will have a greater velocity than one nearer the axle. If now the beam of the balance is pointing exactly west-east, the rotation of the earth, which is in the same direction, will have no tendency to turn the beam to either side. But if the beam is pointing north-south, the rotation of the earth and its force of gravity, which act upon the two masses unequally, will turn the beam horizontally to a slight degree, thus twisting the torsion wire A through a very small angle, which can be measured by the movement of a ray of light reflected from the mirror. Calculations from these measurements will reveal with remarkable accuracy any departure from strict proportionality between inertia and weight,

for the torsion balance is so wondrously sensitive that a variation in the proportion of one part in a hundred million can be detected. It is thus quite as sensitive as the Michelson-Morley apparatus, while the results obtained by its use are probably less susceptible of controversy. With this balance Eötvös found that no difference whatsoever could be detected in the direction of the resultant force W in Fig. 17. For twenty-five years the significance of this experiment remained unperceived until it was interpreted by Einstein as a conclusive proof that the gravitational and inertial masses are not merely proportional to each other, but are identical, so that variation of one apart from the other is inconceivable. This principle he therefore made one of the two physical foundations of his general theory of relativity. The second of his fundamental principles is the assumption that a body moves in the space-time world in a curved path or world-line of such a character that it is a geodesic or the shortest of all possible lines or paths. This second principle has already been discussed.

With such appliances as were at his disposal Newton was able to demonstrate that the gravitational mass of a body was proportional to its inertial mass by experiments which could have detected a difference between them of one pound or one ounce in a thousand pounds or ounces, or, as it is usually expressed, a difference of one part in a thousand. Bessel, in Germany, with much more exact apparatus found the proportionality to be true within the far smaller possible error of one part in sixty thousand. Baron Eötvös, with his extraordinarily delicate torsion balance, has proved the proportionality to be correct with an error not exceeding one part in one hundred million. With this limit of accuracy science at present must be content.

As a consequence of these experimental results, the gravitational mass and the inertial mass of a body are not to be regarded as different properties of matter but as different manifestations of the same property. It follows, therefore, that if the generalized law of inertia of mass in the space-time universe can be found, it must also be the

general law of gravitation. The discovery of this law is the great achievement of Einstein.

Upon careful study of the application of his law, Einstein deduced four tests of its correctness which have received ample verification. The fulfilment of these predictions has elicited the admiration of the world and conferred upon their distinguished author a lofty and imperishable renown.

The most important consequence is the fact that Newton's law itself can be deduced from it by assuming, as a special case, the action of gravitation to be solely confined to the masses of bodies and their distances from each other.

The second and much the most sensational of the three special tests, none of which can be deduced from Newton's law, is the predicted deflection of a ray of light when traversing a gravitational field of force. In Fig. 2, to which reference was made at the commencement of this discussion, the character of the deflection was shown.

As calculated by Einstein, the deviation of a ray of light coming from an infinite distance—a star

—on one side of the sun, then grazing its surface, and finally proceeding to a practically infinite distance—the earth—on the other side, should be 1.745 seconds of arc, the amount becoming less as the ray of light passes the surface of the sun at a gradually increasing distance from it. In more precise terms, the magnitude of the deflection of a ray of starlight inward and the apparent displacement of the star itself outward are inversely proportional to the distance of the light-ray from the centre of the sun. Exactly half of this deflection is due to the force of attraction of the sun and can equally well be deduced from Newton's law; the other half, however, is produced by the geometrical modification or curvature of space caused by the sun and cannot be inferred at all from Newton's law, which contains no terms applicable to this characteristic of gravitation.

The question naturally arises: Why not use the earth instead of the sun as the body deflecting the light? The amount of deviation that a ray of light would experience when passing by the surface of the earth would be far too minute to be

detected, since the force of terrestrial gravitation is relatively very small. When the ray passes the sun it is subjected to a gravitational force 27.6 times as large as that of the earth, owing to the immensely greater solar mass, which is 330,000 times as much as our planet contains. Since a spherical body exercises its attraction as if the whole mass were concentrated at its centre, the radii of the sun and the earth, the former of which is about one hundred times the latter, enter into the calculation of the deviation of light. It may thus be found that the deflection of a ray of star-light by the sun is about three thousand times as great as that which would be caused by the earth. Since the solar deflection is only 1.745 seconds of arc, the deviation due to the earth would be about 0.0006 second of arc, an amount hopelessly beyond the power of measurement by our most refined instruments, even could a place be found in space where they might be located in order to make the observation.

The first of the two astronomical expeditions referred to at the beginning of the discussion

found the displacement of the stars to be 1.61 seconds of arc; the other, 1.98 seconds. The mean of these two values is 1.795 seconds, which is not very different from the theoretical value of 1.745.

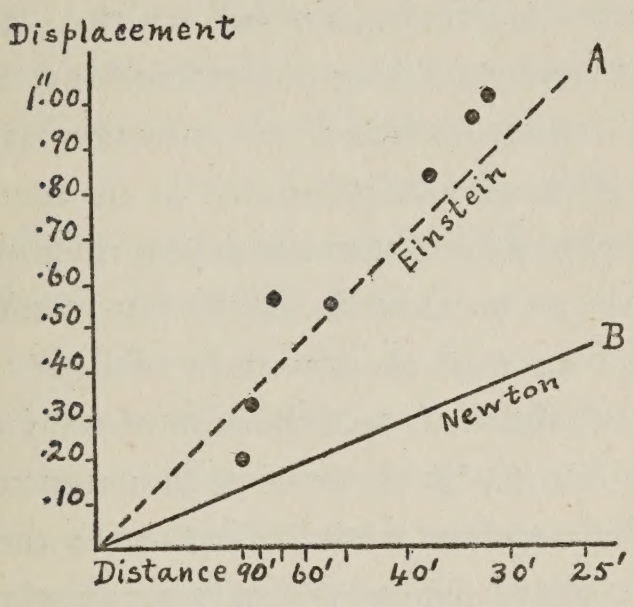

Fig. 19. Radial displacement of stars away from the sun. Eclipse, May 29, 1919. (Eddington.)

In 1922 further observations were made by astronomers of the Lick Observatory, and the mean value of 1.74 seconds was obtained from measurements upon eighty stars. Surely such evidence as this is conclusive by its quality as well as by its quantity. There is reproduced in Fig. 19 a

graphic portrayal of the displacements of several stars given by Eddington. The broken line A indicates the theoretical displacements, and the observed displacements of the stars are shown relatively to this by the black dots. The half displacement according to Newton's law is shown by the continuous line B. No stars at all are to be found along this line.

From considerations such as these it follows that light has mass. It is as legitimate, therefore, to speak of a pound of light as to refer to a pound of any substance. A number of years ago light was sold in Winnipeg by the supply company at the rate of 20 cents per kilowatt-hour, or $2,400,000,000 per pound. Under public ownership the price has been reduced to three cents per unit, or $360,000,000 per pound. By taking advantage of the discount of 10 per cent. for prompt payment, an additional saving of $36,000,000 may be effected on every pound of light we buy!

Eddington has calculated that 160 tons of sunlight fall on the earth each day. At a price of only one cent per unit the daily value of this solar

contribution is $32,000,000,000,000. The sunlight is utilized in preserving all life and in producing food; part is also used in lifting by evaporation about 235 cubic miles of water into the atmosphere each day, a quantity greater, in all probability, than the whole of the material moved by the human race since its beginning.

The second special deduction from Einstein's law of gravitation is concerned with the revolution of the orbit of a planet. When a planet revolves in its elliptical orbit around the sun, which is situated in one of the foci of the ellipse, there will be one position when it will be nearest the sun. The planet is then said to be at perihelion as is shown by position a in Fig. 20. It was discovered in 1845 by the celebrated French astronomer, Leverrier, who at the same time as Adams, made the mathematical discovery of the planet Neptune, one of the great triumphs of the application of Newton's law of gravitation, that the planet Mercury did not arrive at its perihelion exactly at the time it should have completed its orbital revolution, but a little later. This is

equivalent to saying that the major axis of the ellipse itself rotates around the sun in the same sense as that in which the planet itself moves. This

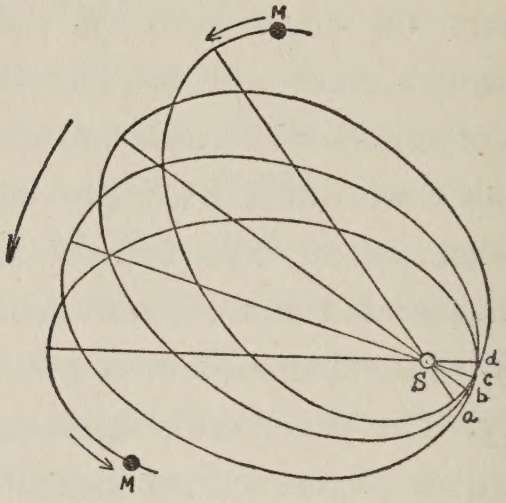

Fig. 20. Revolution of the orbit of Mercury. At successive revolutions of the planet the perihelion positions are a, b, c, d, and so on. The motion of the planet will be appreciated best by placing a pencil at the upper position of M and tracing the path to the lower position of M. The diagram is greatly exaggerated, since over twelve and a half million revolutions of the planet would occur before the orbit would resume its original position.

is shown by the large arrow to the left in Fig. 20. The second perihelion of Mercury is indicated by b. The amount of revolution of the orbit of Mercury, or the advance of its perihelion from a to b,

was calculated by Leverrier, and later by Newcomb, to be at the rate of 43 seconds of arc per century. This indicates that in a little over three million years the major axis of the orbit of Mercury would make one complete revolution. The cause of this motion could not be explained by Newton's law. But Einstein calculated from his more exact theory that every planet's orbit should have a similar motion, and that in the case of Mercury it should amount to exactly 43 seconds per century. The remarkable agreement of the former calculated value with that computed from Einstein's theory affords another complete test of the correctness of his law.

The third special test lies in the deduction from Einstein's theory that an electron emitting light will move more slowly in a strong gravitational field than it does in one that is weak, and the wave of light will be lengthened.

It has been proved that nearly sixty of the ninety-two terrestrial chemical elements are also to be found in the sun. If, therefore, we compare the length of a wave of light from some chemical

element on the earth, where gravitation is weak, with the length of a similar wave of light emitted by the same element situated at the surface of the sun, where gravitation is strong, the latter wave ought to be longer than the former. Therefore light which has a terrestrial wave length of 0.000 038 83 cm. has a wave length on the sun 0.000 000 000 8 cm. longer. This measurement is so small that it lies on the borderland of the impossible. Yet its determination has at length been attended by success, and in this respect also the theory of Einstein has been amply and satisfactorily confirmed.

The progress of astronomical research has unexpectedly reinforced this last test. The white dwarf companion of the very bright double star Sirius, the brightest in our sky, has been found to possess such enormous density that one cubic inch of its substance would weigh a ton. In consequence of its tremendous gravitational force the relativity increase of wave length, which is about thirty times that found on the sun, is so great that its measurement is unmistakable.

Thus we discover that the wave lengths of light emitted by the electronic constituents of an atom are not the rigorously fixed quantities they once were thought to be. Since the lengths are influenced by the strength of the gravitational field in which they originate, they also have only a relative and not an absolute magnitude.

Other applications of these tests could be cited. For the principles governing planetary orbits, shown in the case of Mercury, apply with equal cogency and exactness on the infinitesimal scale to the orbits of electrons within the atom. In the minute study of the structure of the atom also the great variation of mass with the high velocities of the electrons, which was previously discussed, cannot be ignored.

These deductions from Einstein's theory of gravitation have been verified beyond question and carry the confirmation of the truth of the whole concept of relativity.

The theory of relativity throws light upon a curious problem of astronomy, as Eddington has pointed out. Stars are known with diameters over

five hundred times that of the sun, that is, about five hundred million miles. While their volume is enormous, their density lies at the opposite extreme, about a million times less than that of the sun, which again is only a little greater than that of water. Such stars therefore are scarcely denser than the air remaining in a glass tube after an air pump has removed all that can possibly be taken out. This condition is what is usually called a vacuum.

If, however, these super-enormous stars had a density equal only to that of the sun, the force of gravitation would be so great that their light rays could not escape but would fall back upon the surface like a stone to the earth. The stars would consequently be invisible. There must be a critical value of gravitation, therefore, at which the light of a star could neither escape nor return to the surface, but would forever sweep round the orb with ever-accumulating density—a star enveloped with light, yet invisible! Or the waves of the spectrum would be so lengthened by the intensity of gravitation that they would be swept

out of existence, unless there were also generated infinitesimal waves that would be lengthened into visibility to replace them. As a third consequence the mass would produce so much curvature of the space-time would that space itself would close up around it and leave us outside of space, which means nowhere at all!

In pre-relativity days the final consummation of the universe was once suggested to be the accumulation of all the matter of the universe into a single huge mass. If such were to happen, then, as Eddington says, space itself would close up around it, and the whole universe would come to a tragic end by vanishing away.

Reference has been made to the struggle between the supporters of the Ptolemaic and Copernican cosmogonies, which in the experience of Galileo became so intense and relentless. From the standpoint of relativity the controversy now appears quite meaningless, for the same effects that the moving earth exhibits because of its rotation could be produced equally well on a fixed earth by a revolving system of stars.

IS SPACE INFINITE?

Is the universe finite or infinite in extent? The imagination fails to picture the infinite; the finite again is too small to satisfy the mind. The suggestion of a boundary instantly invites the question: What is on the other side? If we suppose both space and the number of stars sprinkled through it to be infinite, it has been shown, from Newton's theory of the world, that a stable solar system such as our own would be impossible. A finite number of stars in illimitable space would wander apart infinitely distant from each other and so be lost. Of the occurrence of these possibilities there is no indication whatever.

According to the principles of relativity the space-time world would be infinite in extent were it not for the presence of matter, which by its gravitational power produces a curvature of the space-time universe. Thus the infinite becomes finite. So definitely has this been accomplished that a world-radius has been computed of the order of magnitude of possibly 150,000,000 light-years.

Curiously enough, the world-radius has no reference to a centre from which in ordinary geometry such a line is measured. In Newton's theory a centre was essential. Einstein, however, contrary to Newton, has discarded altogether the idea of any centre of the universe at all as a "distasteful conception." Possibly, therefore, the universe has a cylindrical structure, a form which seems quite as probable as the conventional spherical shape given it by our imagination.

Since light travels in a curved space-time world it should return to its starting-point after the lapse of many ages, perhaps one hundred million years. If a train of light waves be emitted in some direction for one second, it will constitute thereafter a "streak of light," 186,000 miles in length. As it travels in a curved path it can never reach an edge or boundary of the universe, but ultimately will return to its source from a direction opposite to that in which it was emitted. The universe itself is therefore to be regarded as finite in volume, but with no assignable boundaries; with a definite radius, but no centre.

It has even been suggested that nebulae apparently situated in the remotest depths of space in one direction in the sky are in reality but rear views of the same nebulae seen in the opposite direction, the light during the immense ages of its journey having curved round sufficiently to accomplish that paradoxical effect.

UNITY OF THE LAWS OF NATURE

It has long been the hope of scientists that a single primary law or principle might sometime be discovered which would contain, or be essentially connected with, all other laws of nature, wherein unity of plan might be combined with the most varied application. The three greatest forces of nature, gravitational, magnetic, and electric actions, are especially suggestive of a fundamental unity since they all obey the same type of law, often called the "law of nature," which, to a first approximation at least, may be written,

$$F = k\frac{mm'}{d^2}$$

where m and m′ represent masses, magnetic poles, or electric charges, d is the distance between their centres, and F is the force of attraction and, in the case of the last two, sometimes of repulsion between them. The constant k differs in value in the three different cases.

The magnetic and electric forces were discovered independently of each other, and for a long time no suspicion was entertained of any connection existing between them. In the early part of the nineteenth century two experimental discoveries of great significance were made, one by Oersted in Denmark, in 1820, who found that a magnet could be controlled by an electric current, and the other in 1831 when Faraday in England discovered that an electric current could be generated in a conducting circuit by the motion of a magnet near it. Thus electricity in motion exercised a magnetic force, and magnetism in motion an electromotive force. The unification of these actions so auspiciously begun was consummated some forty-five years later by Maxwell in his general theory wherein both forces appeared as

the components of a single electromagnetic action. Both components are always necessarily present, though one or other may in certain cases be of very small value. Thus in a magnet the electric component of the force is negligible, while with electric charges the magnetic force in its turn is insignificant.

Einstein has now developed an extension of his theory which unites gravitational forces with those of electromagnetism and has applied it successfully to two special theoretical problems. In the interactions of matter with matter, in masses and perhaps in atoms and their parts, the three forces are always associated. Gravitation, the weakest of the three when small masses are concerned, is always present to an invariable extent which cannot be increased or diminished in intensity by any power in our possession. The electromagnetic parts of the action are now under our control, as the modern applications to industry, transportation, and communication abundantly testify. Conceivably this new development may lead to the discovery of some means by which the

intensification and neutralization of gravity may be effected and so fulfil what has seemed to be only a fanciful and impracticable dream. A far more likely result is that tests may be deduced connecting gravity with electromagnetism in some definite way, comparable in importance with the deflection of rays of light, which may afford additional experimental proof of the validity of the theory of relativity. Probably the not distant future will bring a still more fundamental mathematical structure which in addition to uniting gravitation and electromagnetism will comprise all types of physical phenomena in one set of equations. When this is done the long-cherished dream of the unification of the physical world will have been accomplished.

The universe, as Newton and subsequent philosophers conceived it, was a material world of rigorously absolute values immersed in the ether diffused throughout a simple three-dimensional space, with an independently flowing time. Mass, length, and time were invariable under all conditions of rest or motion. It was a vast improvement

over the previous conceptions, and probably will ever remain the practical system employed in all investigations except those involving second order effects.

The profound genius of Einstein has transformed the universe from absolute to relative values. Mass, length, and time are found to be varying magnitudes, changeable with their velocities. The easily conceived three-dimensional world has emerged into one of four dimensions in which time, ceasing to retain independence, is blended with space. Mass becomes identical with energy, inertia with weight. The curvature of the space-time continuum, impressed upon it by matter, reduces the otherwise infinite universe to a finite volume delivering it at the same time from the philosophical embarrassment of boundaries. Nor are we yet at the end of discovery. For even now, as we are struggling to assimilate the principles of relativity, the electrons and protons —the basic fabric of atoms—are being viewed not as material corpuscles but as wave patterns in space. This new conception of matter, whose

consequences cannot yet be fully realized, seems, as remarked before, to avoid some of the contradictions involved in the related properties of matter and space. Evidently we are here confronted with the formidable problems of atomic constitution and structure, the solutions of which, if ever they come, must undoubtedly afford greater precision to our ideas of the operation of the universe in relation to the interactions of its so-called material and spatial domains.

The relationship of space, time, matter, and energy in the new conception of the universe leads to a view of the laws of nature essentially different from that which has hitherto been entertained. The belief has been held that the laws of the universe are more or less independent of each other in the sense that any one of them could arbitrarily be changed without disturbing the rest. The laws of nature might thus have been likened to the furnishings of a house; the furnishings could be altered without destroying or remodelling the house itself. To make the difference in ideas clear in the new philosophy of the universe, an analogy

may be used. The "laws" of a cubical room are: is has eight corners, six sides of equal area, twelve equal edges, and the angles are all right angles. A conservation law might be formulated by saying that the number of these parts is a constant. If the room remains cubical these "laws" are immutable. Should we destroy the cube and construct a spherical room in its place the laws or properties become automatically altered to suit the description of the new room. So the laws of nature that have been so laboriously ascertained are to be regarded as the properties of the universe. To alter any one of them in the slightest degree must necessitate discarding the present universe and substituting a new creation in its stead.

Many will naturally become discouraged in attempting to grasp the strange teachings of relativity. The Newtonian ideas, so revolutionary at their inception, only gradually became the elements of clarified reasoning in science. The same difficulty that we experience when confronted with the new ideas of the world also prevailed when a similar transition became

necessary from the involved conceptions of Ptolemy and of Descartes to the majestic simplicity of the scheme of Newton. Thus we learn from Voltaire, whose essay has been so frequently quoted: "Newton's Philosophy has hitherto seemed to many as unintelligible as that of the Ancients; but the Darkness of the Greeks proceeded from their having in reality no Light at all, whilst that of Newton arises from his Light's being too remote from our Eyes. He has discovered Truths; but he has searched for, and placed them in an Abyss, into which it is necessary to descend, in order to bring them out, and to place them in full Light."

More revolutionary even than Newton's are the doctrines of Einstein, which, though novel to us and elusive to our rigid ways of thinking, may become habitual and perhaps commonplace only to future generations. Space, time, matter, energy, are inextricably united as members one of another. The precise formulation of their relationships is a problem of extraordinary difficulty, as the age-long attempts to solve it by the greatest geniuses

of the race have proved. Probably the basic facts of the far-flung world of nature are even yet unascertained; ultimate truth still awaits discovery. Experience has shown that "from Truth to Truth the human Mind rises insensibly to such sublime Points of Knowledge as seem to be entirely out of its Sphere." Who then is sagacious enough to predict from what source and in what direction the next advance may be made?

When to matter and energy creative power has added life, endowed life with mind, and crowned the whole with spirit, a universe emerges which organically is one in the splendour of its conception and in the correlation of its living with its lifeless parts—a universe in which mind and spirit can at once be immanent and still transcend the fettering limitations of their gross environment.

Here we are confronted with the almost unsearchable facts and doctrines of biology, of philosophy, and of theology which, united with those of the physical world, constitute a universe never grasped in its completeness by any mind, which may be for ever beyond the power of finite intellect to comprehend.

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